Node Network Computer Modelling and a Simple Hand Calculation Compared with Contemporary High Rise Evacuation Case Study Data

by

Garth Hay

Supervised by:

Dr. Michael Spearpoint

Associate Supervisor:

Hamish MacLennan

Fire Engineering Research Thesis

- June 2012 -

A research Thesis in partial fulfilment of the requirements for the degree of Master of Engineering in Fire Engineering at the University of Canterbury

Department of Civil and Natural Resources Engineering

University of Canterbury

Private Bag 4800

Christchurch, New Zealand

Abstract

Tall buildings are becoming more common in the modern built environment and the method of evacuating or moving to a place of safety using the stairs is still the primary means of egress. Typically designers use tools such as computer models and hand calculations to predict the time taken for occupants to evacuate to an exit or place of safety. However, increasing trends of obesity, age and a sedentary lifestyle is raising questions about the accuracy of some of the tools. As the tools are based on case study data carried out in the 1980's.

This research compares evacuation performance of case study buildings to the predictions by Pauls' simplified hand calculation and the EvacuatioNZ computer model. The comparison uses four multi-storey buildings from the case study data, ranging from 11 to 27 stories high. The research will also investigate the effect of how the building is represented in EvacuatioNZ on the performance of the prediction and make recommendations in best practice for further work.

Results from the comparisons shows EvacuatioNZ is within 15% for total egress time of the case study data in six out of eight of the stairs. The average difference of EvacuatioNZ to the case study is 8.6%. Further comparisons of exit flow rate and descent speed show EvacuatioNZ is within 10% of the case study data in five out of eight of the stairs. Paul's simplified hand calculation predicts a total egress time which is 6% to 38% shorter than the case study data. Modifying the equation to equalise stair entry delay improves the prediction to a difference of 0.9% to 31%. The modified equation is within 10% in five out of eight stairs.

The comparisons for EvacuatioNZ indicate predictions which are generally with 10-15%. However individual performance is not investigated and this area should be fully investigated to answer concerns about contemporary occupants and their ability to descend multiple flights of stairs. Further work should include a larger range of data, particularly exploring building height and population.

Given the recommendations are followed and more data becomes available for further work to support this research; EvacuatioNZ could be used as a tool for

predicting evacuations in multi-storey buildings. Pauls' hand calculation is not recommended for predictions of multi-storey evacuations without a safety factor. Differences between the prediction and case study result were improved with a modification of the equation to account for the case study stair entry times.

Acknowledgement

My supervisor Dr. Michael Spearpoint; for signing up for the journey and diligently providing feedback within my erratic schedule.

Co-Supervisor Hamish MacLennan; for providing the case study research and offering support and advice with his great depth of knowledge and experiences.

UoC Lecturer Charley Fleischmann; for instilling me with a passion for fire safety engineering and the in particular the nature of people evacuating during fire emergencies.

Gilbert Gordan and the Christchurch Holmes Fire and Safety team; for giving me a taste of the dark arts of consulting engineering and solidifying my enjoyment for the field and the people within it.

Parents, Trevor and Terry Hay; for being patient and supportive without question, whom without I would have probably never made it this far.

Family, David, Carli and Roger Hay; for instilling me with the determination and admiration to aspire to complete my education to this degree.

New Zealand Fire Service commission; for providing scholarships and support to the course and degree at the University of Canterbury.

Arup Fire Australia; for providing scholarship support during my time as a student which greatly relieved the pressure.

Craig Hiscock from Parsons Brinkerhoff; for inspiring and providing motivation for me to finish my thesis and become a Fire Engineer.

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1 Introduction

1.1 Introduction

Buildings of today are becoming taller than those from last century, tall buildings can now range from 10 stories to well over 100 stories. During emergencies the primary response is to evacuate the building and in the tall buildings of today, the challenge is moving the potentially large populations down many floors to a safe place within an acceptable time period. This typically involves isolated safe stairs and in some cases, lifts as well.

Designers of tall buildings not only need to consider the time taken for occupants to travel from their location to an exit out of the building or to a place of safety, but also the delay from hearing the alarm to initiating that travel. Travel down stairs can often be the main factor in the time taken to escape, however in buildings with lower, more scattered populations or where people may be sleeping the pre-evacuation delay before they begin to travel towards an escape can be the determining factor for the time taken to escape.

Many modern buildings have lifts installed and lifts have been investigated as an alternative method of evacuation (Groner and Levin, 1992; Bukowski, 2008; Heyes, 2009). However, in older buildings or where training might not be sufficient it is difficult to overcome traditional avoidance of lifts (Heyes, 2009). Before being included as a means of escape lifts need to be designed to protect against failure, smoke, require specialised emergency programming and be encased in fire resisting shafts.

The data used for stair movement dates back to the 1970's and 80's, when Pauls (1987) and Fruin (1987) collected case study data of multiple tall buildings over several years. Pauls' proposed hand calculation methods to predict multi-storey building evacuation times based on the case study data. In modern design, advanced computer models are now commonly used and many of these are based on, or often validated against the original 1980's methods. The difficulty in collecting more recent detailed case study data and the limited range of buildings in the original data compared to what is built today, results in mostly intra-model validation. The reliability of this practice comes into question if the original data is deemed inappropriate for contemporary buildings and occupants.

There are concerns that the original data might be invalid (Pauls 2007) due to global trends in first world countries of increased obesity, old age and a more sedentary life style which might be causing a general lack of fitness. This concern primarily focuses on these changing characteristics and the increase in the number of occupants in taller buildings, and the possible influence this could be having on contemporary performance relative to Pauls' and Fruin's original research.

Recent video case study data was carried out on a range of tall buildings in Australia, United Arab Emirates, New Zealand and the United Kingdom. This research intends to develop best practice methods for node network modelling of multi-storey buildings based on this case study data. The research will then investigate differences between the node network computer model, a hand calculation method developed by Pauls and the case study results.

1.1.1 Objective

The objective of this research is to make comparisons between the case study results, a Monte Carlo network model and a hand calculation method from the original case study research. This explores the differences in performance between contemporary occupants and some design tools used to predict the evacuation performance for a multi-storey building. The research has two specific focuses;

1) An improved method of representing stairs in a node network model is validated using the case study data. This ensures the computer model is working as intended and provides recommendations of input choices for future modelling efforts.

2) The model's prediction results are compared to case study results and hand calculation methods developed by Pauls for predicting multi-storey evacuation. This will contribute to current research on the concern of the degrading performance of contemporary occupants.

The Monte Carlo network model used for this research is EvacuatioNZ in development at the University of Canterbury.

1.2 Background

Multi-storey buildings are becoming a significant factor of the living and working lives of people in contemporary society. At the start of the 20th century, the tallest building was 119 m high, the Park Row Building, Manhattan (Bukowski, 2009). Now, buildings are being built over a 100 floors and 500+ m high with the tallest building currently being the Burj Khalifa with 163 floors and standing 828 m high (Skyscraperpage.com). Correspondingly, the number of occupants within a single building is also increasing.

Fire safety design for these tall buildings needs to consider many variables to achieve the primary focus of life safety. Traditionally, to achieve life safety for occupants in a building during an emergency the building would be fully evacuated. Modern buildings however, will sometimes involve lifts, safe places (refuge floors) spaced down the building height, or non-evacuation procedures. It is reasonable to expect that into the future, evacuations from tall buildings will likely continue to involve at least in part, descending multiple flights of stairs to an exit from the building.

1.1.2 Stairs

Stairs in buildings come in several types, and while some of the geometric design is often regulated such as width and stair treads dimensions, many other factors will vary between buildings. There are three general types of stairs commonly found in most buildings; scissor, dogleg and spiral.

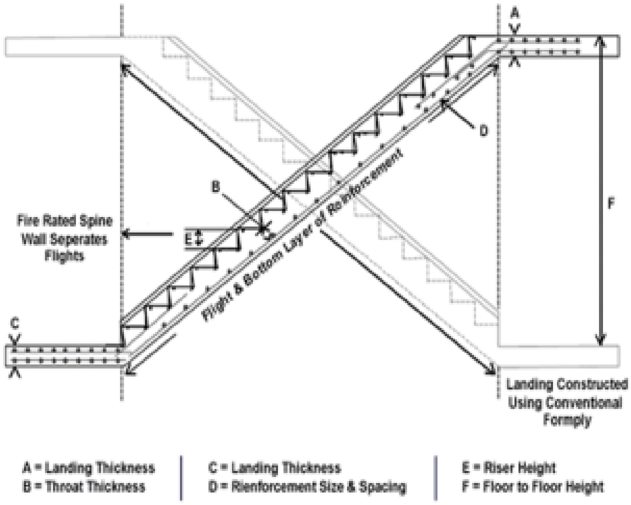

Figure 1: Elevation of Scissor Staircase Design (stairform.co.au)

A scissor stair case design (Figure 1) involves a straight flight from one floor to the next. Entry doors will alternate the side of the stairwell each floor. Scissor stairs are typically enclosed with a wall between flights rather than a space, but this is not always the case. These stairs are often used to save space as they are only large in the length dimension. But, the long continuous flights are sometimes considered physically more difficult when descending relative to other stair designs.

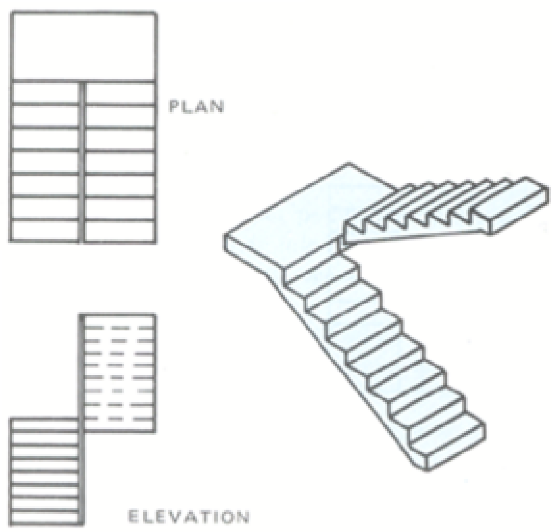

Figure 2: Dogleg or Half Landing Staircase Design (build-home-house.com)

The dogleg or half landing design (Figure 2) has a mid-flight landing located part way down the rise, with two 90° turns before a second flight to the next floor. Entry doors to this type of stair will therefore always be on the same side of the staircase. A gap can be present between the flights as an open stairwell, or they could be separated by a wall with no opening, as an enclosed stairwell. Dogleg stairs benefit from having a mid-flight landing in terms of allowing extra space for resting or passing of slower movers.

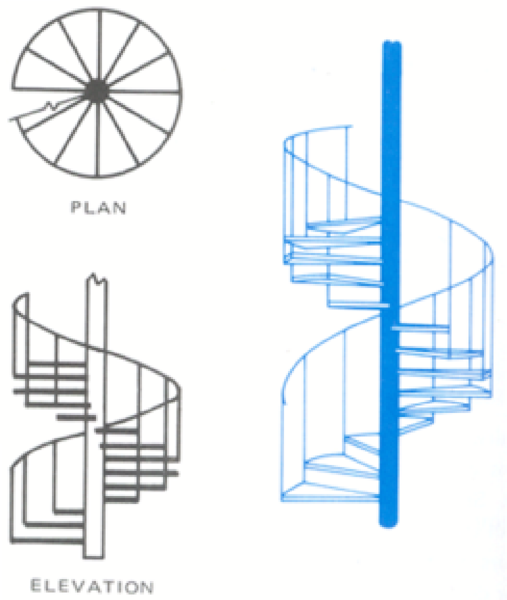

Figure 3: Helical Spiral Stair with Central Spine (build-home-house.com)

A spiral stair design (Figure 3) is typically a rounded stair with a continuous curve around a central spine, although there are also square shaped spiral stairs. These stairs often include an open space in the central area of the stairs for aesthetics and an open back (hollow) stair riser design. A curved spiral staircase would not often be found in a multi-storey building as one of the egress stairs, as they are often steeper and challenging to descend for those unsure of their balance. The non-uniform tread width also reduces the capacity of the stair and is especially difficult in counter-flow situations.

1.1.3 Occupants

Occupants and their ability to descend stairs is an important factor in the performance of an evacuation in a tall building. The change in characteristics of modern occupants compared to those of occupants 30 years ago is a particular concern for researchers and designers. The question currently is whether contemporary occupants are performing worse than case study occupants from decades earlier due to obesity, age and decreased fitness from a sedentary lifestyle.

Obesity in contemporary society has been increasing and nearly twice as many people were classified as obese in 2008 compared to 1980 (BBC News, 2011) where obesity is categorised from overweight to morbidly obese based on body mass index (BMI). BMI is a method of classification for excess body fat in people using the total weight divided by the height squared, where overweight is defined by the World Health Organisation (WHO) as a body mass index (BMI) over 25 kg/m^2.

Obesity is linked to chronic health conditions (Rand, 2007) but is still not currently considered a disability (WHO). There is evidence within health literature that obesity is linked to limitations of a person's ability (He and Baker, 2004). Evacuation research has also attempted to find a link between obesity and decreased descent speed, some finding little correlation (Galea et al. 2008.). While, other research suggests that total egress times will increase if trends of age and higher proportions of obese occupants in buildings continue (Spearpoint and MacLennan, 2012).

A sedentary lifestyle can also impact on a person's ability to evacuate, and contemporary people are becoming increasingly sedentary (Booth et al, 2002). The less active people are, the less fit and able they are to descend multiple flights of stairs. Averill et al. (2005) found that many evacuees from the World Trade Centre Towers "were totally unprepared for the physical challenge of the evacuation with many of them having to rest during descent". More detailed research on the number of floors contemporary occupants could physically cope with descending is currently unavailable.

Conclusive research on the effect of either of these conditions or other factors of change to occupant characteristics is yet to be carried out. However, the hypothesis is that contemporary occupants are expected to perform worse than the case study occupants from the last century.

1.1.4 Computer Models

The use of computer based evacuation models saves time and cost when modelling complex egress scenarios such as multi-storey buildings when compared to carrying out trial evacuations. Designers use computer models to predict performance in a range of worst case scenarios. Researchers and investigators aim to simulate case study events as closely as possible.

Many models represent occupants in an egress simulation as agents. Modern models can now direct agents with sophisticated algorithms not only of people movement but also psychological factors such as motivation and personality. Some models can also include the influence of fire and smoke on agents. As the level of complexity of outputs increase, the detail of inputs required also increases.

There are several models which have been developed for egress simulation. Fahy (2003) in her study characterised the models that were available into three categories; single parameter estimation models, movement models and behavioural movement models. The single parameter model estimates the total evacuation time using simple egress approximations. Movement and behavioural movement models are both ball bearing type algorithms, which allow for larger populations and more complex geometry while sacrificing some agency. The behavioural models allow for further definition of individuals' agency, and their responses to the environment.

To ensure that computer models produce results which are reliable and useable in design and research, comprehensive validation is required. Ideally validation is carried out against case study data and Gwynne and Galea (1998) suggests the ideal situation is multiple sets of detailed data from a case study building, sampled at different times.

The ideal case study data comes from evacuation information during real fires and emergencies. However, such events are rare, and as a result trial evacuations are the accepted alternative form of case study data. The assumption being that a real fire or emergency evacuation will occur with most occupants being unaware of the hazard and therefore behave in a similar way to a trial. Trial evacuation data is rare because organising trial evacuations and collecting detailed data is a costly and difficult process.

1.3 Literature Review

1.1.5 Evacuation from Tall Buildings

The most crucial case study research of recent history in terms of multi-storey building evacuation is the September 11 World Trade centre (WTC) disaster. Where an estimated 17,400 people were in the two buildings at the time of the aircraft impacts. This was roughly half of an estimated potential 40,000 people in each building at capacity (Pauls, 2002). A large investigation of all facets of the disaster followed, including the evacuation.

NIST's (Averill et al, 2005) final report on the investigation resulted in 30 broad recommendations for improving building safety. Some of these were relevant to egress, fire protection and notification;

- Improve active fire protection systems to provide performance, reliability and redundancy
- Improve the evacuation process to facilitate safe and rapid egress; methods for ensuring clear and timely emergency communications to occupants; and better occupant preparedness for evacuation during emergencies
- Maximise the remoteness of egress components without unduly increasing travel distances
- Design tall buildings to accommodate a total building evacuation of all occupants if necessary

The last recommendation, in a given building might take considerable time to achieve. Factors like the range of ability of the population in descending stairs as well as the number and capacity of the stairs, will have a significant impact on the total length of time taken to evacuate, particularly in a tall, densely populated building.

The need to rest while descending multiple flights of stairs to evacuate could slow egress within the stairs further. Tubbs (2009) suggests that occupants might struggle to descend more than 40 floors at a time and issues could arise with larger proportions of people needing to rest during an evacuation of buildings higher than this, and subsequently slowing people behind them who cannot pass when the stairs are narrow. This is referred to as a 'plug' effect.

MacLennan et al. (2008) suggests the mere act of even having to descend multiple flights of stairs, especially in tall buildings, is a safety hazard represented by falls, trips or other injuries from exertion. This applies to a range of people, but particularly the older, more obese or unfit occupants. The awareness of, or limitation due to this hazard for some can influence and slow their descent rate. This can contribute to an artificial increase in stair density due to the plug effect.

A more recent case study by Peacock et al (2009) using video analysis in stairwells of a several multi-storey buildings concluded that descent speed is influenced by variables beyond those which are quantified in current engineering calculations. While the research concluded people were not moving slower, current engineering variables accounted for only 13% of variation in descent speed. Implying the ability to predict evacuation performance in taller buildings with occupants who may have different characteristics to those of previous case studies would be difficult with current methods.

1.1.6 Pre-evacuation Times for Multi-storey buildings

Evacuation can be subdivided in four components; three for delay time (Fahy, 2003) and one for egress travel (Proulx, 2002). Fahy divided delay time into "time to notification", "reaction time" and "pre-evacuation activity time". After this "pre-evacuation" delay period occupants are considered to be travelling towards an exit, which may be interrupted by actions such as resting or investigating before being resumed. Pre-evacuation is an important factor of evacuation time but is difficult to quantify.

Pre-evacuation delay for occupants can vary from a few seconds to tens of minutes. The cause for long delays can be due to people who do not acknowledge there is an emergency, people who do not hear the alarm (Proulx, 1995) or people are sleeping. Very long delays can be the longest component in an evacuation of a building, particularly if there are few occupants or distances to travel are short.

Kuligowski (2008) suggests that research and development for evacuation computer models focus too much on predicting evacuation movement while ignoring the detail of pre-evacuation behaviour. Kuligowski suggests further work on the inclusion of robust, comprehensive and validated theory on human behaviour during evacuation.

1.1.7 Travelling Down Stairs

Egress travel time has been the focus of many studies and computer modelling software. Often the egress travel is the major factor in the time taken to evacuate a multi-storey building, and there are two primary phases for this stage of the evacuation. The first phase is travel time to the stair, consisting of the time taken for an occupant to reach the stair after deciding to evacuate the building. The second phase consists of the time taken to descend the stairs to the exit or place of safety.

Time taken to travel to the stairs and down the stairs can be limited by a number of geometric and / or environmental variables and occupant characteristics. The main factors are typically considered to be distance, widths and number of doors and stairs, and the width of the paths plus the speed at which occupants will travel.

Several studies have recorded or estimated descent speeds in stairwells. Table 1 below shows a summary of speeds recorded for descending stairs (Peacock et al, 2009) for a range of ages and / or travel densities.

Table 1: Table of Various Occupant Movement Speeds in Stairwells (cited from Peacock et al, 2009)

Year	Movement Speed (m/s)	Notes	Source
	0.52 ± 0.24[a]	18-29 year old	Various [b], from Lord et al. (2005)
	0.52 ± 0.23	30 – 50 year old	Various [b], from Lord et al. (2005)
	0.49 ± 0.18	> 50 year old	Various [b], from Lord et al. (2005)
	0.16 – 0.76	Disabled occupant	Various [b], from Lord et al. (2005)
1969	0.58 ± 0.15		Predtechenskii and Milinskii[c] (1978)
1972	0.762	Maximum	Fruin (1987) from Pauls (1995)
1972	0.6096	Moderate	Fruin (1987) from Pauls (1995)
1972	0.4826	Optimum	Fruin (1987) from Pauls (1995)
1972	0.2032	Crush	Fruin (1987) from Pauls (1995)
1988	0.33 ± 0.16	Locomotion disability	Boyce, et al. (1999)
1988	0.7 ± 0.26		Boyce, et al. (1999)
1995	1.1	Relatively fit	Proulx (1995)
1995	0.5		Proulx (1995)
2001	0.2	9/11 WTC towers	Averill et al. (2005)
2004	0.76 – 1.3	Varied walking angle	Fujiyama (2004) adapted by Hostikka[d] (2007)
2007	0.57 ± 0.23	Photo luminescent stairwell markings	Proulx (2007)
2007	0.64		Hostikka (2007)

a - uncertainties are expressed as one standard deviation

b – includes data from Fruin (1987), Predtechenskii and Milinskii (1978), Boyce et al. (1999), Proulx (1995), Proulx et al. (1999), Fahy and Proulx (2001) and Webber (2001)

c – includes movement speeds for densities the authors define as typical for stairwell evacuation

d – data converted from horizontal speed to speed along the incline with given stair geometry

Occupant descent speeds down stairs are affected by a number of factors. The typical factors to consider are density in the stairway, depth of tread, height of the riser, the angle of the stairway and presence of handrails (Gwynne and Rosenbaum, 2008). Several other factors are also considered to influence occupant descent, physiological ability, psychological factors such as fear of falling and incidental factors such as or people carrying objects (children, coats or pets etc)(Pauls, 1987; Proulx, 1995).

The factors which influence the descent speed can be distinguished into two broad categories. The first is engineering variables which have been approximated with a numerical influence on stairwell movement. The second is behavioural and physiological factors. Peacock et al. (2009) have suggested that these factors may have a significant influence on the variance in stair descent speed amongst recent studies, where engineering variables were demonstrated to have limited influence. This contributes to the concerns that previous case study data is no longer relevant.

1.1.8 Regulations for Stair Widths

The regulation requirements for buildings have evolved over time to some extent along with the buildings as they become taller and contain more occupants. Current regulations for stairs in multi-storey buildings typically determine the stair width in relation to the number of occupants expected to use the stair, referred to as stair capacity. Most regulations will define a minimum width for these stairs even for low occupant floors.

Stair widths across different regulations (Bukowski, 2009) generally range from 1000 mm (Australia, United Kingdom) to an 1100 mm minimum (United States, Hong Kong) plus a determinate number of mm/person based on the total occupant population served by the stair. This ranges from 5 mm/person to 10/11 mm/person, and can sometimes also be dependent on the number of floors in the building to descend (Spain/EU, China).

1400 mm (56 in) is the newly recommended minimum stair width (Bukowski, 2009), which allows for people to descend two abreast comfortably instead of in a staggered pattern. A 1400 mm width also allows for effective stair usage, especially in counter flow situations and for the wider occupants of contemporary society (Templar, cited by Bukowski, 2009).

Some regulations will also define minimum treads and risers (Bukowski 2009), for example the Hong Kong building regulations specify a minimum tread of 225 mm and a maximum riser of 175 mm. Whereas Australian building regulations define a minimum tread of 250 mm and a maximum riser of 190 mm.

2 Case Study Buildings

Comparison to case study data is the primary principle of this research. Seven buildings were studied during trial evacuations by MacLennan as part of his research into inclusive design for stairs.

The basic geometry of the buildings used for this research and the resulting data are summarised in this chapter.

2.1 Research by MacLennan

Recent case study data was collected by MacLennan (2011) to investigate inclusive design in stairs. MacLennan's research is aimed to investigate the risk of falls and other issues of safety relating to people's ability to descend stairs. The case studies involved recording trial evacuations of high-rise buildings using cameras in the stairwells.

The evacuations were announced trials carried out on regular business days. Cameras were placed in the stairwells, and in some buildings observers were present on some floors and participated in the trial evacuation. The cameras were placed on most or all the stairwell landings. In certain buildings this was not possible due to a limit of cameras, cameras failing to properly record or being dislodged. Since the video cameras were placed on landings within the stairs, there was no data available on occupant actions prior to entering the stairs.

MacLennan also carried out post-evacuation voluntary questionnaires to determine the characteristics, health, fitness and psychological values of occupants using the stairs. The questionnaire data is available alongside the camera data but was not used in this research. This was because privacy issues made it difficult to associate the two datasets sufficiently to complement the comparisons.

The data is for seven case study buildings located in the United Kingdom, Australia, Dubai and New Zealand. Building heights ranged from 10 storeys to 32 storeys and most were office type buildings, which did not involve the public or people unfamiliar with the building. No buildings were noted to have sleeping occupancies.

Three buildings were excluded from the comparison in this research due to the camera recording data missing some parts of the descent of the occupants. The number of occupants requiring extrapolation for detailed descent times was larger than is reasonable for comparison purposes.

2.2 Manchester Building

This is a 17 storey building located in Manchester, The United Kingdom. The building has a rectangular shape floor plan. The floor plan as shown in Figure 4 (MacLennan, 2011) gives the floor area as 27 m by 12 m with both stairs located on the same long facing of the building.

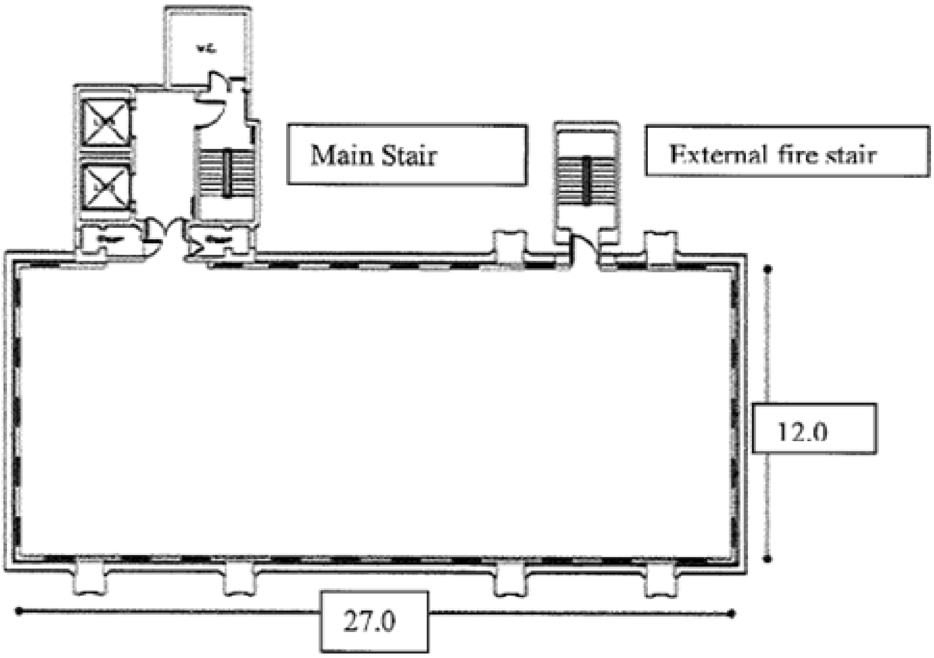

Figure 4: Manchester Building Plan (MacLennan, 2011)

The stair on the left denoted as "clean stair" is the primary means of egress. The second set of stairs denoted "Dirty stair" is limited for use as an emergency fire stair and is located in an enclosed external structural element from the building. The "Clean stair" has another door which leads to a room "wc", it is assumed it does not affect the evacuation as it is likely a water closet. Lifts are present and were not used by the occupants recorded in the video footage of the evacuation.

2.2.1 Primary "Clean" Stairs

The primary stairs are referred to as the "Clean stairs" within the data and this naming convention will be used throughout the research.

The stair is a rectangular dogleg type stair (Figure 5), measuring approximately 2.25 m across and 5.1 m long. The entry door has a width of 1.07 m, and swings into the stairwell but away from the flights. Figure 5 shows each flight has a different width measurement of 940 mm and 960 mm respectively.

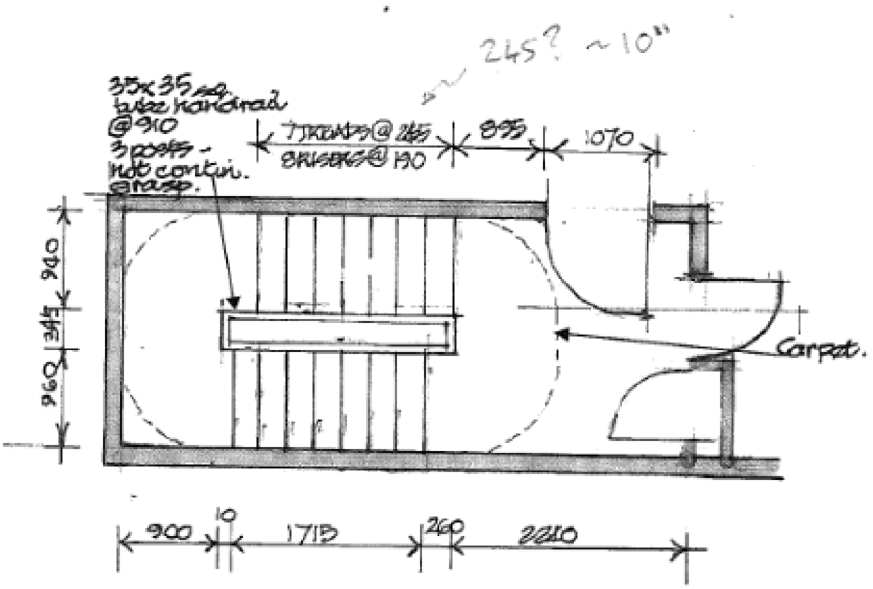

Figure 5: Manchester "Clean Stair" Plan (MacLennan, 2011)

The tread is indicated as 245 mm and the riser is 190 mm. No information is given about the nosing. The stairs and landings are noted as being carpeted. The horizontal flight length is shown to 1.98 m and the length of the mid landing is 2.25 m. The height of both stair flights is 3.04 m which is confirmed by the number and height of the risers.

The handrail is a 35 x 35 mm rounded square which sits at 910 mm above foot level. The handrail is not a continuous grasp with each section supported by three posts. Gaps were noted to be present at the corners. The distance the handrail's project onto the stair is not given.

The camera footage data notes 171 unique occupants. At least three of these occupants were noted as observers for the study. Six occupants were missing full data on the descent.

One of the three observers and two other occupants, who are potentially wardens, were located on the 10^{th} floor. These three occupants had very long stair entry times; 320 – 450 seconds (~5 – 7.5 minutes). It is uncertain what caused this long delay but this did not occur in any other building and significantly impacted the total egress time, adding 2 minutes to the bulk egress time.

Due to the effect the three occupants had on total egress time and the long entry times resulting in them descending practically empty stairs they have been excluded in the further analysis. Therefore, 168 occupants will be used in any comparisons.

2.2.2 Secondary "Dirty" Stairs

The secondary stairs or external stairs are referred to as "Dirty stairs" within the data in the same manner as the main stairs. This is in reference to the appearance of the stairs and in particular the walls and floors which appear "very dusty" (MacLennan, 2011) combined with minimal lighting/emergency lighting.

These stairs are also a rectangular dogleg type stair (Figure 6), measuring approximately 2.35 m across and 4.2 m long. The entry door has a width of 1.05 m, and is located in a very short corridor, slightly wider than the door, which connects the stairwell element to the building.

Figure 6 shows the flight width as 975 mm. It is worth noting that this stairwell has spacious landings relative to the flights of stairs. In this research it is assumed that this will not significantly add to the travel distance of the occupants, but the extra space may better allow passing or resting.

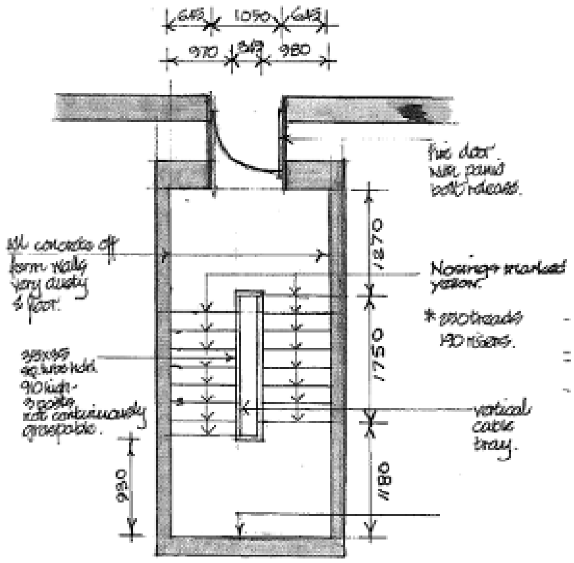

Figure 6: Manchester "Dirty" Stair Plan – Diagram not to Scale

The tread is indicated as 250 mm and the riser is 190 mm. It is noted that the tread nosing are marked in yellow. Floors are noted to be concrete with no carpet or other covering. Each flight has a horizontal length 1.75 m and the landing length is 2.35 m long. The descent height is 3.04 m, like the clean stair and is confirmed by the number and height of the risers.

The handrail is a 35 x 35 mm rounded square which sits at 910 mm above foot level. The handrail is not a continuous grasp with each section supported by three posts. Gaps were noted to be present at the corners. The distance the handrail's project onto the stair is not given.

The camera footage data notes 79 unique occupants. All occupants have full data.

2.3 Majestic Building

This is an office building in Wellington, New Zealand, located on a sloping site. The building is 29 stories high with two basement levels, serviced by two stairs, one which services 23 floors, and the other which services 27 floors. Figure 7 shows the lower 2 floors are car parking and retail areas and since these are not found within the data it is assumed these floors have direct exit routes from the building. The 27 floors found in the case study are office type occupancies serviced by the two internal stairs.

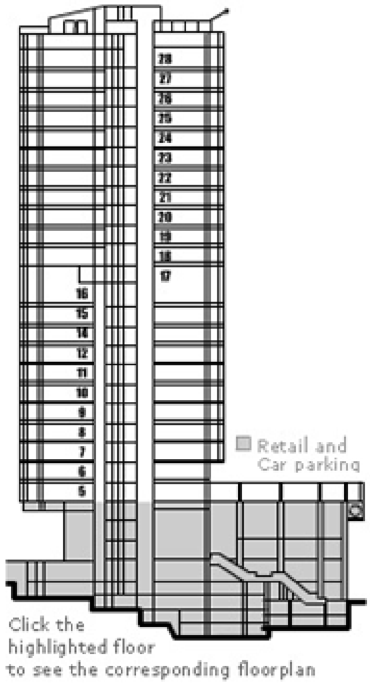

Figure 7: Majestic Building Elevation (www.majesticcentre.co.nz)

The floor plan (Figure 8) does not give specific floor layouts, but shows the building has a semi circular facade on one side with a squared facade on the other. The area of office space is roughly equal on all sides of the stairs.

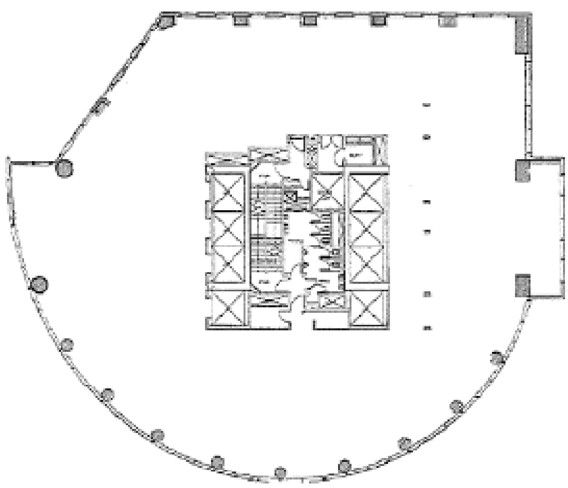

Figure 8: Majestic Floor Plan (MacLennan, 2011)

Figure 9 shows both of the stairs which are a straight flight scissor type stairs with a mid-landing. Both stairs are located within a core structural element located in the centroid of the building; therefore it is difficult to determine which stair is identified in the data. This is unlikely to be of importance however as the stairs are identical in dimensions. Lifts are present and were not used by the occupants recorded in the video footage of the evacuation.

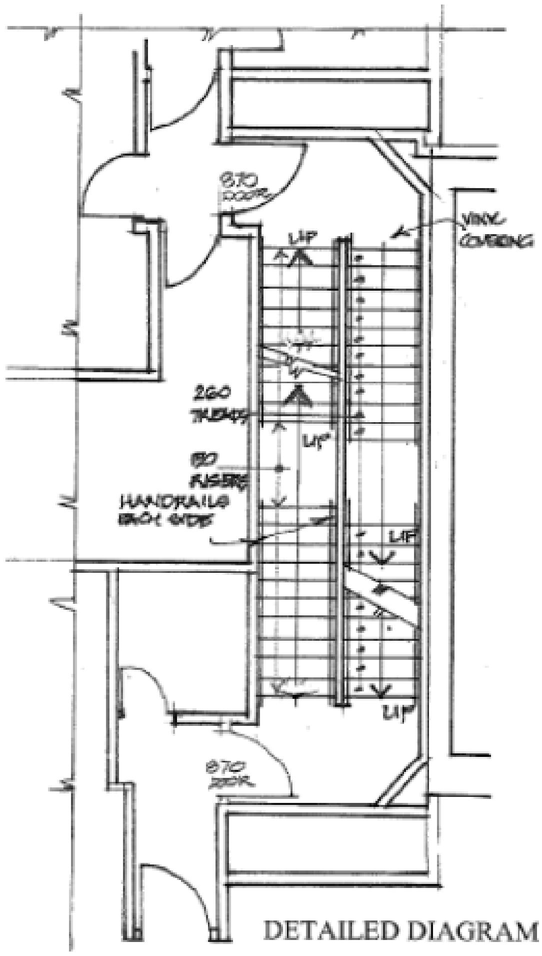

Figure 9: Majestic Stair Plan (MacLennan, 2011)

2.3.1 Stair One "Main Stair"

Stair one services the uppermost 23 floors of the building before reaching an exit. This stair is referred to as "Main Stair" in the data but it is not specified exactly why.

The straight type scissor configuration means that the stair is a single flight to the next level with no dog-leg requiring occupants to turn. There is an intermediate landing between floors in addition to the landing present on each floor.

The straight flight sections of the stair are measured to have a width of 1.0 m from Figure 9, this is based on the given dimension for the entry door as 870 mm and assuming the drawing is to scale. The intermediate landing can then be inferred as 1.0 m x 1.0 m and thus the main landing is 2.2 m x 1.0 m.

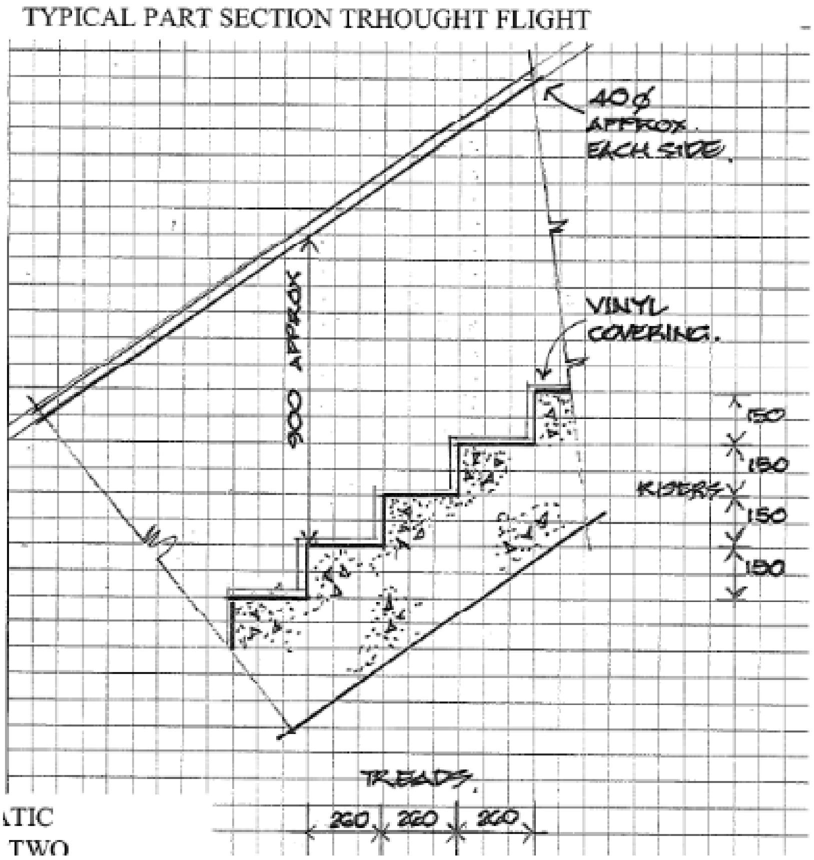

Figure 10: Majestic Stair Cross Section (MacLennan, 2011)

The tread (Figure 10) is 260 mm and the riser is shown as 150 mm. It is noted that the stairs have a vinyl covering, with no indication on the presence of nosing or not. The majestic building is noted as having a descent height of 3.86 m (MacLennan, 2011), therefore each flight has 13 risers. The horizontal length for each flight is calculated to be 3.4 m. The mid-landing has a measured length of 1.0 m

The handrail is a 40 mm diameter tube which sits at approximately 900 mm above foot level. It is not specified if the handrail is continuous but it is shown in Figure 10 as being present on both sides of the stair the entire length of the flights but not on the landings. The distance the handrail's project onto the stair is not given.

The camera footage data notes 377 unique occupants. There were 2 observers amongst those descending. Otherwise, full data is available on all occupants.

2.3.2 Stair Two "Basement Stair"

The only difference between the "Basement" and "Main" stairs is that this stair services all 27 office floors. The additional four floors proceed to a lower exit than the "Main stair".

This stair is referenced as "Basement stair" and is presumably due to the lower exit. This stair has identical dimensions to the "Main stair" as described above.

The camera footage data notes 302 unique occupants. Full data is available on all occupants.

2.4 Unisys

Unisys is a second office building located in Wellington, New Zealand. This is a 17 storey high building serviced by two stairs located to one side. The general floor shape of the building is a slender rectangle as can be seen in Figure 11. Lifts are present but it is not mentioned if they are used during the evacuation, it is assumed they are not.

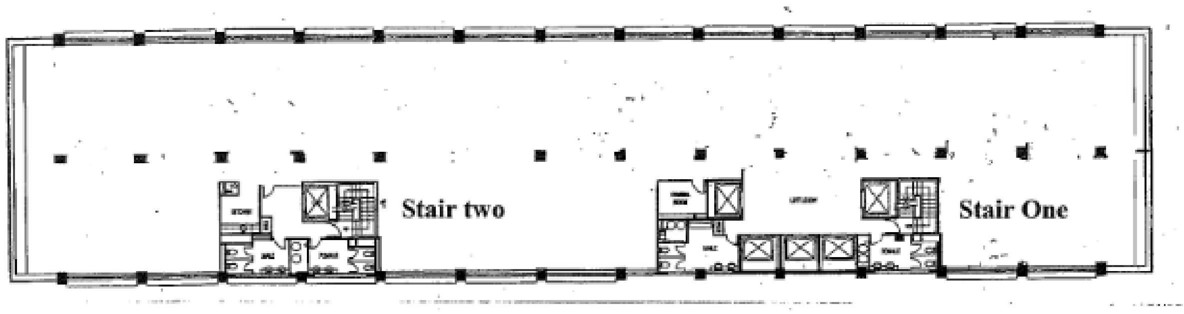

Figure 11: Unisys Floor Plan (MacLennan, 2011)

Both stairs have similar dimensions (Figure 11) with a double half-turn type stair for occupants with short flights and two mid-landings between each floor landing. The entry door swings into a small corridor.

2.4.1 Stair One "East Stair"

Stair one and two are named based on their location in the building. Both stairs have a vertical well in the central cavity. It is not specified if the cavity is open or enclosed with walls.

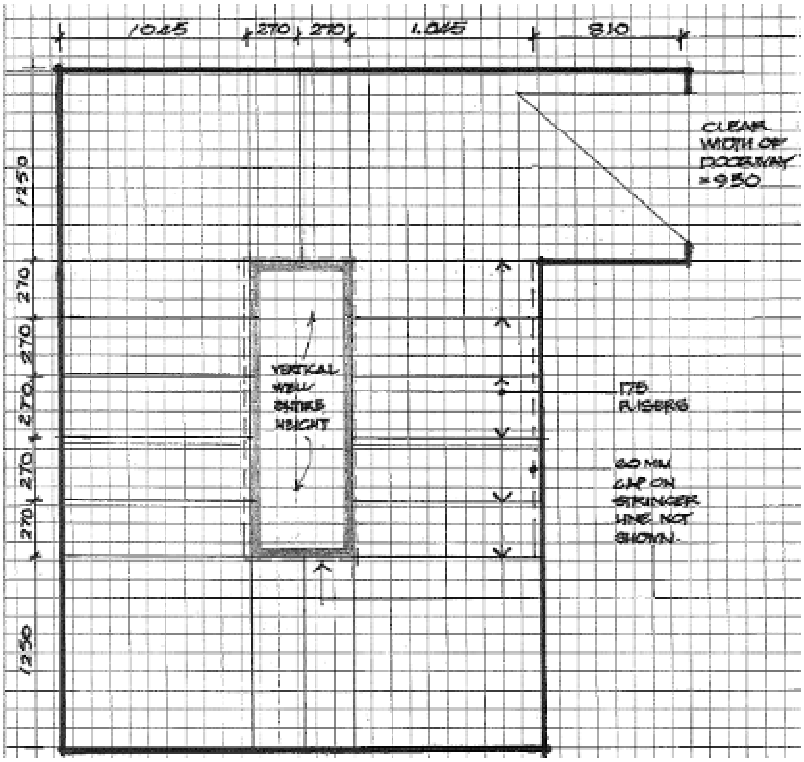

Figure 12: Unisys Building Stair Plan (MacLennan, 2011)

The longer flights (Figure 12) consist of 5 treads for a total of 1.35 m with a width of 1.045 m. All four of the landings are square with the dimensions of 1.045 m x 1.250 m. The short flights consist of 2 treads for a length of 540 mm and a width of 1.250 m.

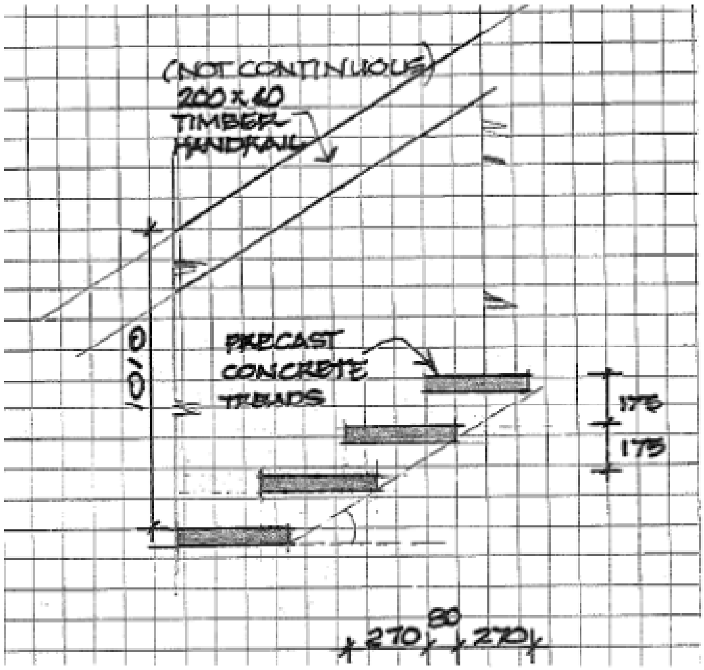

Figure 13: Unisys Stair Cross section (MacLennan, 2011)

Figure 13 shows the clear tread length is 270 mm and the riser is shown as 175 mm. The stairs consist of precast concrete treads which have open back gaps in the risers. The horizontal length for the long flights is 1.35 m and the short flights are 0.54 m each. The landing length is 1.045 m. The descent height of 3.0 m and is confirmed by the number and height of the risers shown.

The handrails are specified as non-continuous 200 mm x 40 mm square timber handholds. The handrail is positioned 1000 mm above the foot position. The distance the handrail's project onto the stair is not given.

The data recorded 312 occupants using the stair. There were four observers and at least one recorded warden as part of the evacuation.

2.4.2 Stair Two – "West Stair"

Dimensionally, the "West" stair is identical to the "East" stair described above. The only noticeable difference from the information given is the presence of lifts and a lobby outside the East stair. The West stair has one lift adjacent but none of the recorded occupants used this during the trial evacuation.

The data gives 255 occupants using this stair. The data notes two wardens on each floor.

2.5 Christchurch

This was an office building located in central Christchurch city, New Zealand prior to the February 2011 earthquake, the future of the building is still uncertain at the time of writing. This was an 11 storey building with a rectangular shape, serviced by two stairs which were roughly centrally located.

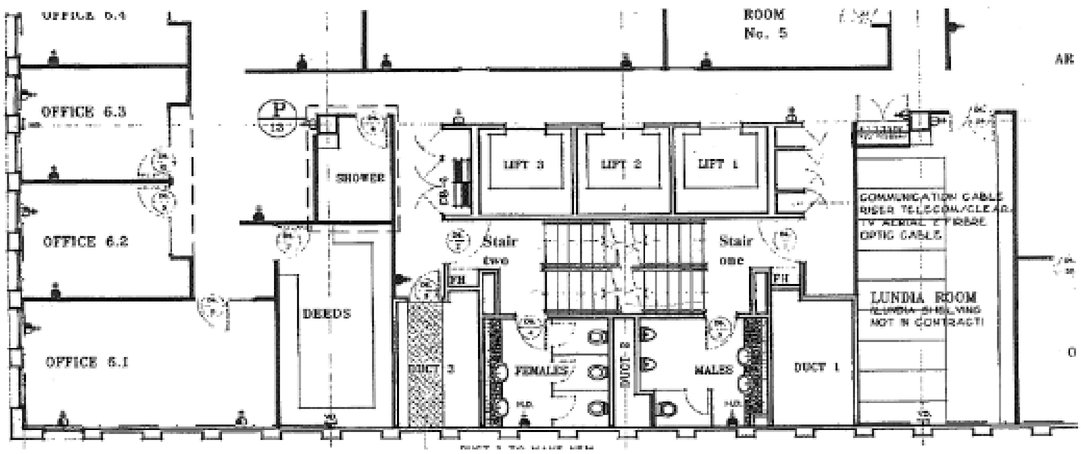

Figure 14: Part Floor Plan of Building in Christchurch (MacLennan, 2011)

The typical floor layout for the building (Figure 14) has parts of the plans omitted but this includes more offices similar to the central and west side rooms. The dimensions of the building are not known from the case study data. Lifts are present but none of the recorded occupants use them during the trial evacuation.

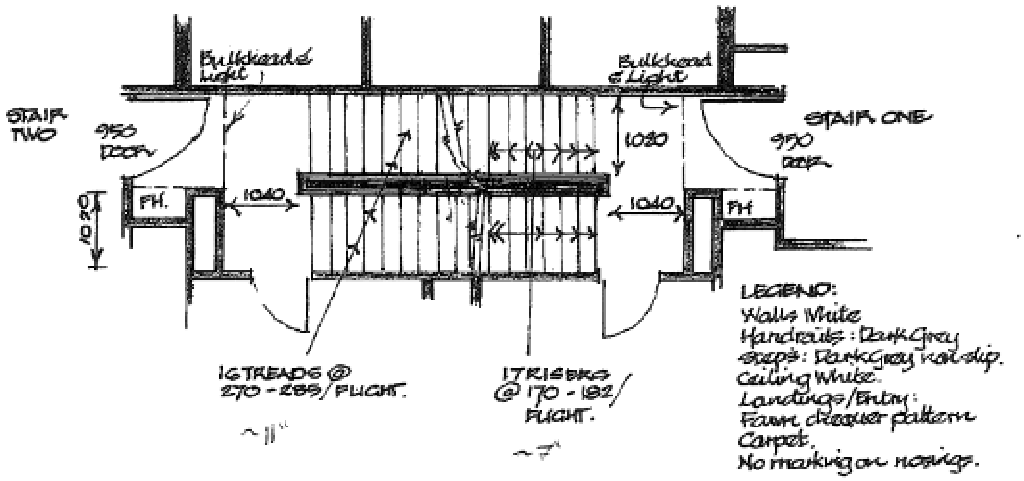

Figure 15: Christchurch Stair Plan (MacLennan, 2011)

The stairs are a scissor type stair (Figure 15) with no mid-landing. The two stairs are positioned adjacent to each other within the building. It is not specified which stair is which, but both stairs are dimensionally similar on the plans.

2.5.1 Stair "A" One

The stairs in the Christchurch building were not descriptively named, using A and B instead. The research maintains these names for consistency.

The total length of the landing is 2.58 m with a width of 1.07 m. The stairs have a width of 1.02 m (Figure 15).

The tread and risers are recorded as a range of values in Figure 15; the average is taken to be 280 mm for tread length, and 175 mm for the riser. The stairs are described as dark grey with textured "non-slip" nosings. The horizontal length of each flight is 4.5 m with no mid-landing. The descent height of 3.0 m and is confirmed by the number and height of the risers.

The handrails are 60 mm diameter semi rounded with a rectangular lower section. These handrails are located 1.05 m above foot level and located on both sides of the stair, they are continuous down the length of the stairs but do not round the corners. The distance the handrail's project onto the stair is not given.

The data gives 88 occupants using this stair. One observer is noted in the data descending with the occupants.

2.5.2 Stair “B” Two

Dimensionally, Stair Two is assumed to be similar to Stair One as no further data is given on any difference.

The data gives 115 occupants using this stair. Three observers are noted descending the stairs with occupants.

2.6 Case Study Data

Case study data was recorded in spreadsheets for each building stair. These spreadsheets were created by an analyst viewing the footage and noting the location of individuals as they descended the stairs.

It is noted that most of the trial evacuations have wardens, observers or both recorded descending the stairs. These people were in some cases one of the last few, or the very last, to leave a floor and in some cases this influences the resultant total evacuation time. However, since actual evacuations during fire or other life safety events may still involve wardens or pseudo-wardens clearing floors it will be stated if a quoted case study evacuation time includes these occupants or not, and this will be considered in any discussion on the results.

2.6.1 Data Format

The case study data came in a simple form of a list of stair landings where a camera was located and a row of individuals observed during the evacuation recordings. The time an individual was seen on a camera was recorded to the appropriate landing (landing observation time). A typical camera position is shown in Figure 16.

Figure 16: Typical Camera Position Showing Stair Landing from Behind the Entry Door (MacLennan, 2011)

The occupant populations for each floor is found within the camera data by grouping all the occupants by starting floor, it is assumed that when a person is first seen on a camera that they originated from that floor. It is not certain how likely it is for people to 'skip' a camera and be seen on floors below but the scale and impact of such an error is considered negligible.

The time of the trial evacuation is noted, however further information on day or month is not given. Landing observation times are converted to a zero start time format for ease of processing. The time of day for each building is summarised in Table 2.

Table 2: Case Study Trial Evacuation Time of Day Summary

Building	Time
Manchester	11:00 am
Majestic	10:45 am
Unisys	9:30 am
Christchurch	10:50 am

2.6.2 Stair Entry

Due to the position of the camera within the stairwell and no additional cameras present within the building there is no data on the occupants before they enter the stairwell. Thus the results present only two distinct stages;

1. Time taken to reach the stairs, which includes the phases of delay time as well as any travel and queuing done prior to entering the stair

2. Time taken to descend the stairs and reach the exit landing

The overall distribution of stair entry times found in the case study data can be approximated by a normal distribution. This is shown in Figure 17 below.

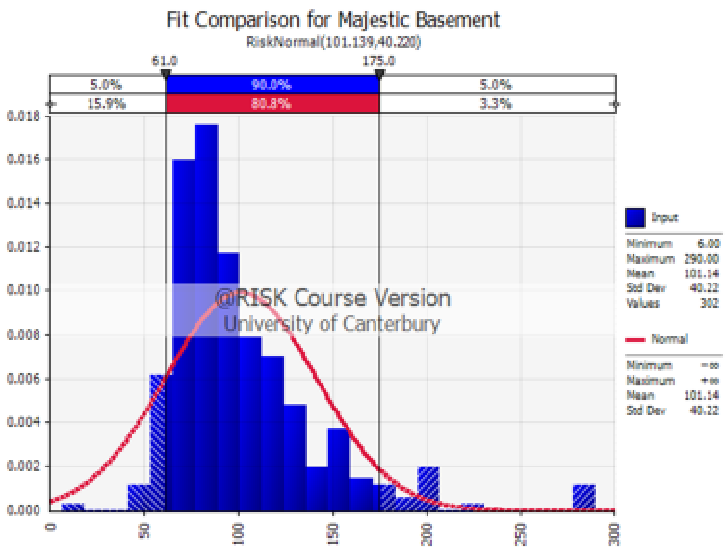

Figure 17: Majestic "Basement Stair" Entry Times Normal Distribution Fit (@RISK)

Similar results are achieved with log-normal distribution (Figure 18) which is more appropriate for the discrete data in the time domain. However, mean and standard deviation results were within 5 s in all the building cases used for this research. The data appears to suit the normal distribution, as long as the normal distribution is truncated at time equals zero. Using a normal distribution for stair entry time is expected to be a reasonable representation. More detail on stair entry time plots can be found in Appendix II.

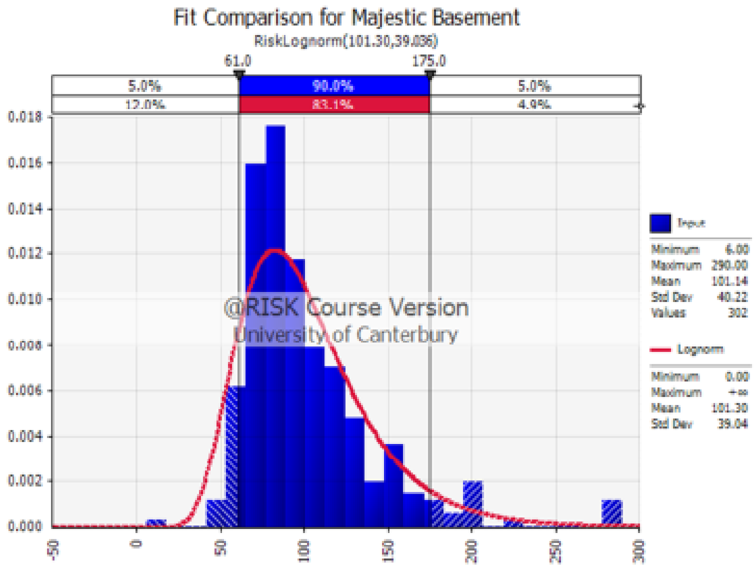

Figure 18: Majestic "Basement Stair" Entry Times Log-normal Distribution Fit (@RISK)

Stair entry times presented as standard distributions for each building are summarised in Table 3 below based on a normal distribution approximation. These values were calculated using the stair entry data from every floor.

Table 3: Total Stair Population Stair Entry Time Distributions

Building	Stair	Average (sec)	Standard Deviation (sec)
Manchester	Clean Stair	77.1	±31.8
	Dirty Stair	63.5	±21.0
Majestic	Main Stair	93.7	±48.2
	Basement Stair	101.1	±40.2
Unisys	East Stair	75.8	±49.9
	West Stair	90.1	±65.0
Christchurch	Stair A	58.0	±23.9
	Stair B	68.4	±33.9

2.6.3 Total Evacuation Time

The evacuation of the building as referred to in this data only represents the time at which occupants reach the exit landing, or what is assumed to be the exit landing. No mention is made if the bottom camera was recording the exit door / path and therefore it is assumed that the occupants have evacuated at this point and it is uncertain whether queuing occurs is uncertain.

Total evacuation times and stair populations are summarised in Table 4 below.

Table 4: Case Study Evacuation Times

Building	Stair	Total Egress Time	Population
Manchester	Clean Stair	351*	168*
	Dirty Stair	321	79
Majestic	Main Stair	583	377
	Basement Stair	637	302
Unisys	West Stair	531	255
	East Stair	542	312
Christchurch	Stair A	216	88
	Stair B	301	122

**This is an adjusted value; see section 2.2 on the Manchester "Clean" stair*

Note that exit landings were not always located on the lowest floor in the building. This can often be the case in buildings which are located on sloping sites. In most cases further detail is not provided as to the exact means of escape once occupants left the last recorded landing.

3 EvacuatioNZ Model

EvacuatioNZ is the computer model used for simulation in this research. The model is described in detail including the main functions and input / outputs which are relevant to the research.

Further information about EvacuatioNZ can be found on the homepage (www2.civil.canterbury.ac.nz/spearpoint/evacuationz). The current version of ENZ used during this research was 2.0.

3.1 Description

EvacuatioNZ (ENZ) is a Monte Carlo based coarse network model for evacuation of buildings. Buildings are represented by nodes which are connected by arcs. The nodes represent building spaces while the connecting arcs represent the paths taken by agents. ENZ is under ongoing development at The University of Canterbury.

Use of a coarse network model to represent the model reduces computational times of the model. ENZ has the ability to employ normal, log-normal, uniform, triangular or Weibull distributions for many of the input parameters and the distributions can be truncated at upper or lower limits specified by the user. Running many simulations of a single scenario gives a range of possible results for the user to consider.

Individual occupants are represented by agents in the model with their own behavioural and personal attributes. The user can specify many these characteristics, including age, sex, BMI and walking speed. However, the model does not account for increased size of agents with higher BMI and the impact this might have. Exit route choices are made by agents, and the user can specify preferential behaviour for exits or total path length. Many of the options have defaults based on accepted literature and is discussed further in Section 3.2.1.

3.1.1 Movement Algorithm

Agent movement speed is based on equations provided by Gwynne and Rosenbaum (2008) and modifiers to an agents speed are based on the effective width concept. An agent's movement speed (equation 1) is a function of the density of the constriction they are in, and a factor (*k*) representing the type of constriction; e.g. door, corridor or stair. If no constriction is specified, the model assumes a corridor.

$$S = k - akD \qquad \text{(Eq 1)}$$

Where;
S = speed along line of travel (m/s)
D = occupant density per unit area (people/m²)
a = 0.266 for SI units
k = constant from Table 5

Table 5: Constants (k) for Equation 1, in SI units from Gwynne and Rosenbaum (2008)

Exit Route Element		k
Corridor, Aisle, Ramp, Doorway		1.4
Stairs		
Riser (mm)	Tread (mm)	
190	254	1.00
178	280	1.08
165	305	1.16
165	330	1.23

Dimensions are rounded to the nearest integer

Table 5 shows that certain building elements modify an agent's speed by more or less. Stair movement speeds are modified based on the tread and riser configurations and Gwynne and Rosenbaum (2008) provide a range of typical stair configurations. They also indicate that the k factor is proportionally approximate to the square root of the tread to riser ratio, and this is how ENZ calculates k.

Doorways in ENZ use a flow rate calculation, where the user must specify them maximum specific flow (people/m [effective width]/s). Agents will pass at the normal calculated speed if the flow rate is less than the allowed flow for a given door. However, if the number of agents attempting to pass through a door exceeds the maximum specific flow, queuing will occur.

3.1.2 User Interface

ENZ does not have a packaged interface, the user creates XML code for parameters and defining the node network. However, a freely available flow chart editor program, yEd (yEd website) using a 'graphml' format, can be used to create the node network which ENZ will recognise. yEd saves considerable time due to ENZ reading directly from the graphml format and allows a visualisation for larger networks, as can be seen in Figure 19 below.

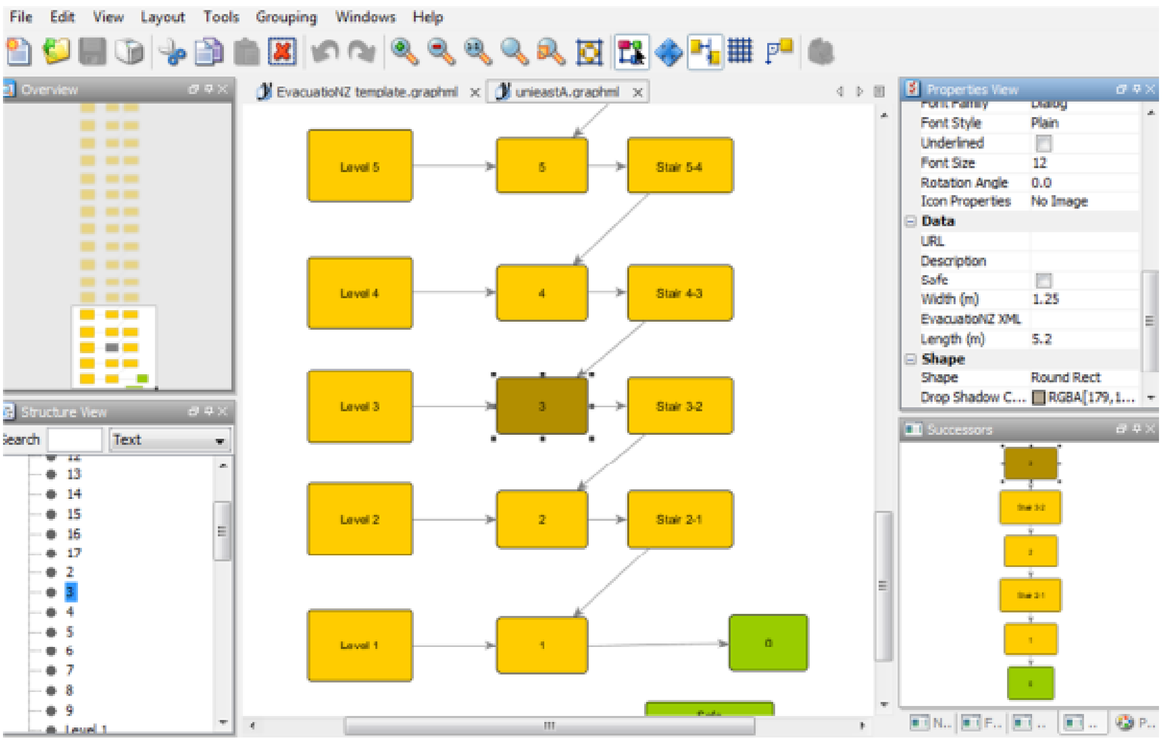

Figure 19: yEd Interface Showing a Node Network

3.1.3 Verification

The model has been verified for a range of simple conditions by Spearpoint (2009) and of particular relevance are the stair flow and tread and riser verification. While not carried out on multiple flights of stairs, the work by Spearpoint demonstrates that the model uses these equations correctly and predicts results similar to accepted hand calculation methods or another computer model.

ENZ has also had recent verification for more complex scenarios such as an Industrial complex (Ko 2007) and a high rise building by Tsai (2007). Many of the limitations pointed out by Tsai and Ko have been improved upon in updates of the model since and are not discussed here.

Tsai analysed the performance of ENZ versus a range of evacuation models on a 21 and a 13 storey building, and reached conclusions on the effect of representing a building space differently. Importantly, concerning modelling stairs Tsai identified the need to investigate how to properly represent long or multiple stair flights in ENZ.

Tsai's comments focussed on representing standing space correctly. In his research he represented stairs with the node as a landing and the arc for the stair lengths. He found that the stairs required a node as well to allow for agent standing space when the stairs became crowded, as arc connections did not 'hold' agents. Tsai suggested representing the stair and landing area with a single node with equivalent dimensions.

3.2 Function

ENZ uses a series of nodes to represent the building space in which agents traverse to evacuate. Each node is linked to another with a 'connector' and a node can be connected to multiple nodes (Figure 20). Nodes are defined by a length and width while connectors have a length and characteristics which will define agent movement. Connectors or arcs are where the effects of constrictions such as doors, corridors and stairs are applied.

The arcs between nodes define the movement time for an agent to reach the next node. Arcs connect the nodes from centre to centre, and require a specified length and width. An arc length of 0 will default to the sum of the length and width of origin node and target node. Therefore, the minimum length for an arc is 0.1 m. The arc width defaults to the average of the length and width of the target node unless specifically defined by the user.

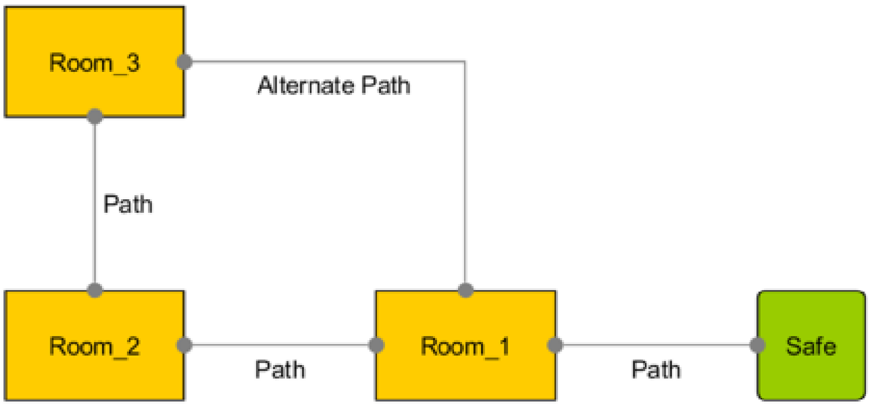

Figure 20: Example of a Simple Node Network in yEd

Each network must have at least one 'safe node', which is used to represent the agents exiting the building or otherwise considered safe for the purposes of evacuation (Figure 20). A network can have multiple safe nodes, and the user can specify certain safe nodes to be preferred by occupants to represent a main or familiar exit.

Node populations are constrained by a maximum occupant density, typically 2.75 people per metre squared, and the model will not exceed this. Connectors do not hold occupants as such, and are only used to determine the speed and distance of travel for an agent to reach the next node. The model does not specifically track an agent's position in a node but they are assigned a starting position, which can be specified by the user. Starting positions influence the time taken to reach the first target connector.

When a target node is full and there are multiple agents from one or more nodes attempting to enter the node, the agent's will wait for a space to open up. Once there is a free space in the target node, the model will randomly choose a waiting agent. If queuing is present, agents who arrived earlier are weighted to have significantly higher probability of being chosen.

ENZ is a time based model which computes changing conditions at set time intervals, typically referred to as time steps. The time taken to navigate constrictions for a given agent is recalculated every time step as the densities around the agent vary. The program also updates the locations of agents and conditions within the model at predetermined intervals during the simulation. This can have the effect of rounding up the time taken for an agent to reach an adjacent node. Smaller time steps increase the computational time required for each simulation while decreasing rounding effects.

3.2.1 Inputs and Outputs

ENZ requires a group of XML files for a project to determine the input parameters of the model. These files are used in a specific hierarchy by the ENZ model, with lower files referenced in upper files (Figure 21).

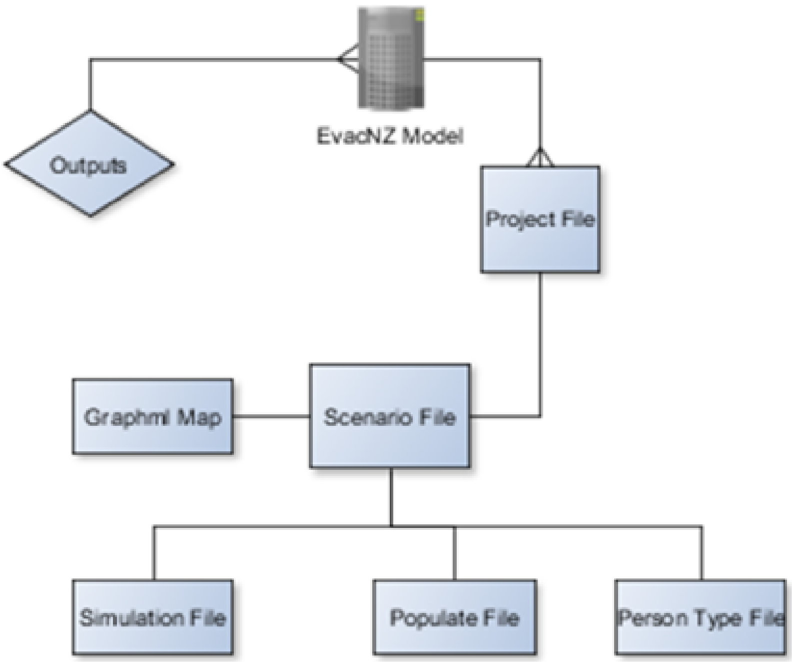

Figure 21: EvacuatioNZ File Hierarchy

Project.xml

This file is the first file read by the executable file for the model and determines which scenarios are executed. The folder location of a scenario file is specified by the user. The selection of which scenarios are modelled is controlled by a simple true/false statement.

Scenario

This is the primary file pointer for a specific scenario, and directs ENZ to the necessary input files for that scenario. The main files used are simulation, person type and populate.

The scenario file is also used to set the number of simulations and a convergence threshold. The location and type of outputs are also specified here.

A convergence feature allows the user to carry out a large number of simulations and have the model stop simulating once the running average of the total egress time changes by less than a specified threshold. This was used successfully by Spearpoint and MacLennan (2012) and this research uses Spearpoint and MacLennan's 0.05% value as the threshold.

Simulation

This file controls the maximum simulation time the model will run until, and what size time step to use. The default time step is 1 second.

Person Type

The person type file allows the user to specify all the characteristics of an agent or group of agents, including age, gender and BMI. The user can also specify pre-evacuation times, as a single number or distribution. Direct egress performance factors including exit preferences and maximum walking speed can be specified.

ENZ defaults to not using age, gender or BMI. If no exit behaviour is selected the default is shortest (total) distance to safe node. Agent speeds are recommended to be 1.2 m/s, if no value is chosen the model conservatively defaults to 0.2 m/s. Pre-evacuation time conservatively defaults to 1800 s if nothing is specified.

Populate

The populate file is used to specify which nodes agents are placed in as their starting point. The user can define which person types are present and the proportion as a percentage, if multiple person types are used.

Groups of agents can be allocated in nodes individually or randomly distributed across a group of nodes by the model. The user can specify a set number of occupants per node, or define the maximum population for a group of nodes and then have the model randomly distribute them before each simulation.

Outputs

ENZ has a large range of outputs available to the user, and for this summary only the outputs used in this research will be commented on.

An output flag needs to be created for any result data the user wants to be saved after the simulations, the following outputs were used for this research;

- Pre-evacuation times

Prints out a comma separated list (csv) of individual pre-evacuation times for every simulation. This was used as a check that the distributions correctly implemented into the model. These values were the case study stair entry times as discussed in Chapter 2.

- Total egress times

Prints out a csv list of egress times for each simulation.

- Node population data as a function of time

This produces a spreadsheet of every agent in a given simulation and their node position at every time step. Additionally, this output also creates another spreadsheet with every node and the number of agents occupying them at every time step.

While this data required some processing, the output can be used to present individual agent descent down the stairs.

- ‘Min-max’ node populations for whole series of simulations

This output processes all the node population data from all the simulations of a scenario. This produces a spreadsheet with every node, similar to the above output but with a minimum and maximum population for each node. These correspond to the minimum/maximum population at each time step across all time steps.

Note: A simulation which is finished will stop being counted for minimum/maximum populations in further time steps

- Agent decision making tracking

This flag produces an html output file for every occupant documenting the decision making and status of every occupant. Status notifications included waiting (pre-movement), queuing or moving at a specified speed (and why).

- Agent (occupant) summaries

This outputs a summary table of populations and starting densities in each node. This feature ensured that distributed and specified node population functions were working as intended.

4 Sensitivity Modelling

EvacuatioNZ was used to carry out simulations of the case study buildings after a sensitivity analysis to determine an appropriate method to represent the buildings in a node network.

The results from the model are presented in three formats; total egress time, cumulative population escaped charts and individual descent charts. These were compared to the case study data.

4.1 Modelling Considerations

Chapter 2 describes the buildings as detailed as possible based on the plans, notes and discussions with MacLennan. Specific assumptions made about the layout for the purposes of modelling in ENZ are detailed below.

4.1.1 Exclusion of Occupants

In many of the case study buildings there were some occupants who were specifically noted as being evacuation wardens. There were also observers amongst the building population as part of the research team for the evacuation. Often, the wardens, and in some cases the observers would be some of the last occupants to begin descending the stairs. The presence of wardens and their behaviour is described in Chapter 2.

During most trial evacuations and real fire emergencies there is likely to be wardens as part of the management strategy. Therefore, these occupants were included in the results and in most cases these occupants were on the long end of the stair entry distribution, but in most cases these occupants did not skew the average significantly.

The Manchester Clean Stair's building wardens had stair entry times around 5 minutes. The result of which not only skewed the stair entry distribution but increased the total evacuation time, as most occupants had already exited the stair before these occupants entered them. As a result it was deemed appropriate to exclude these occupants for comparison purposes.

Comparison to Manchester Clean Stair case study results will use the total egress time of 351 seconds for all occupants excluding the wardens who had stair entries of around 300 seconds. Graphical results will still include these occupants for completeness as the 351 second point is easily distinguishable.

4.1.2 Travel Distance Estimation

Hoskins (2012) in his paper recently discussed the importance of stating and using the correct measurement when approximating movement down stairs. ENZ uses the hydraulic flow method from the SFPE Handbook (Gwynne and Rosenbaum, 2008). As a result, the travel length is defined by the line of travel down the slope of the stairs. Hoskins (2012) provides an equation for the estimation of slope length based on the tread and riser dimensions (Equation 2).

$$L_{T,s} = n(d^2 + h^2)^{0.5} \qquad \text{(Eq 2)}$$

Where;

$L_{T,s}$ *is the stair slope length*

n is the number of treads

d the tread depth

h the riser

The landing travel distance is taken as the length of the landing, which is the linear distance to travel. This is also assumed to approximate the average distance taken to round the landing when negotiating a 90° turn.

Total travel distance (Table 6) is calculated as the distance from centre of one floor landing to the centre of the floor landing on the next floor down. This is the sum of the distance along one floor landing plus all the flights and mid-landings (if any are present) between the two floor landings.

Table 6: Travel Distances Along Line of Travel (Stair Slope) for Each Stair

Building	Stair	Flight Length per flight (m)	Mid-landing Length (m)	Total Travel Distance (m)
Manchester	Clean Stair	2.17	2.25	8.74
	Dirty Stair	2.2	2.35	9.10
Majestic	Main Stair	3.75	1.0	9.70
	Basement Stair	3.75	1.0	9.70
Unisys	East Stair	2.25 (2 flights)[a]	2.1 (2 mid-landings)[a]	8.70
	West Stair	2.25 (2 flights)[a]	1.05 (2 mid-landings)[a]	8.70
Christchurch	Stair A	5.22	No landing	7.26
	Stair B	5.22	No landing	7.26

[a]: The Unisys stair is represented as a two flights and one landing per stair therefore the case study landing and flight lengths have been merged

4.1.3 Effective Width Method

EvacuatioNZ uses the effective width method as described by Gwynne and Rosenbaum (2008). However, the model does not include the calculation for the presence of handrails.

The effective width for a corridor or stair is calculated by including a boundary layer. The boundary layer for a wall is 150 mm. However, if the boundary is a handrail without a wall the layer is 90 mm to account that the shoulder can overhang the handrail. However, if the handrail is attached to a wall the boundary layer is calculated as the largest of;

a) 90 mm + handrail distance from the wall or;

b) 150 mm

EvacuatioNZ does not currently carry out the above calculation as the user cannot specify a handrail or wall boundary for corridors and stairs. However, the 0.15m boundary layer is considered acceptable in the current case study data for two main reasons;

1. There is always one wall boundary, but the other boundary is not specified if a wall is present or not and therefore it is assumed there is a wall

2. The distance of the handrail is not specified, and is unlikely to result in values much larger or smaller than the 0.15m assumption for both layers

4.1.4 Assumptions and Abstractions Due to Data Format

Typically, stairwells have doors separating the stair from the floor level and there is also a door at the bottom of the stairs before occupants exit the building or reach a safe place, i.e. where they are considered safe in regards to life safety. The quantitative understanding of door flow has undergone much change throughout the years of egress research. Door floor can be seen as an important factor in the total evacuation of the building as they often serve as pinch points for flow.

For the case study buildings however, occupants were observed from within the stairwell, and it is not mentioned if occupants are seen passing through doors or if queuing occurs. For comparison purposes therefore, door constriction on the connections between floor and landing nodes and landing and exit nodes were not modelled. It is assumed that the quoted times for egress of the case study is determined by occupants reaching the last landing in the stairwell.

The pre-evacuation time data for occupants is also affected by the observation methodology. Occupants were observed once they had entered the stairwell as described in Chapter 2. Therefore, for comparative purposes in the modelling the pre-evacuation times used were the stair entry times from the data. The modelled evacuation scenarios are of the stairs only and agents are moved from their starting floor to the stair landing immediately using minimum connection lengths of 0.1 m, and a relatively large specified width of at least 10 m to prevent any delays due to queuing.

4.2 Sensitivity Analysis

The sensitivity of the model was carried out based on two of the four case study buildings; The Majestic and Manchester. These buildings were chosen for the relative simplicity of the stair geometry. In addition, each of the stairs in both buildings is unique, thus allowing for essentially four stairs for sensitivity comparison.

The sensitivity analysis was on four variables considered important for this research;

1. Model time step selection: varying between 1 s, 0.5 s and 0.1 s
2. Tread and risers: Assessing the equation used by ENZ to calculate the k factor for tread and risers of stair flights outside values provided by Gwynne and Rosenbaum (2008)
3. Geometric variable: Analysing three methods of node representation of stairs based on comments by Tsai (2007)
4. Agent parameter input variation: Investigating the influence of randomised inputs vs. single values when many simulations of the same scenario are modelled

Recommendations for the further comparative modelling was done on the basis of best fit to the case study data while giving consideration for the detail of inputs required and computational effort.

4.2.1 Time Step

Using the default time step of 1s for this node network model has a rounding artefact which can artificially increase the time taken for an agent to reach the next node. For example, if an occupant would reach a node at 1.1 s, the model will only move the agent to the new node once it reaches the next time step after another 0.9 s. Given a simulation could have multiple agents, nodes and time steps this addition can become significant.

The time step analysis compares the performance of the model using time steps of 1 s, 0.5 s and 0.1 s. The results are summarised in Figure 22 and Figure 23 below, tabulated results can be found in Appendix III. Results are in the form of total evacuation time for a given time step.

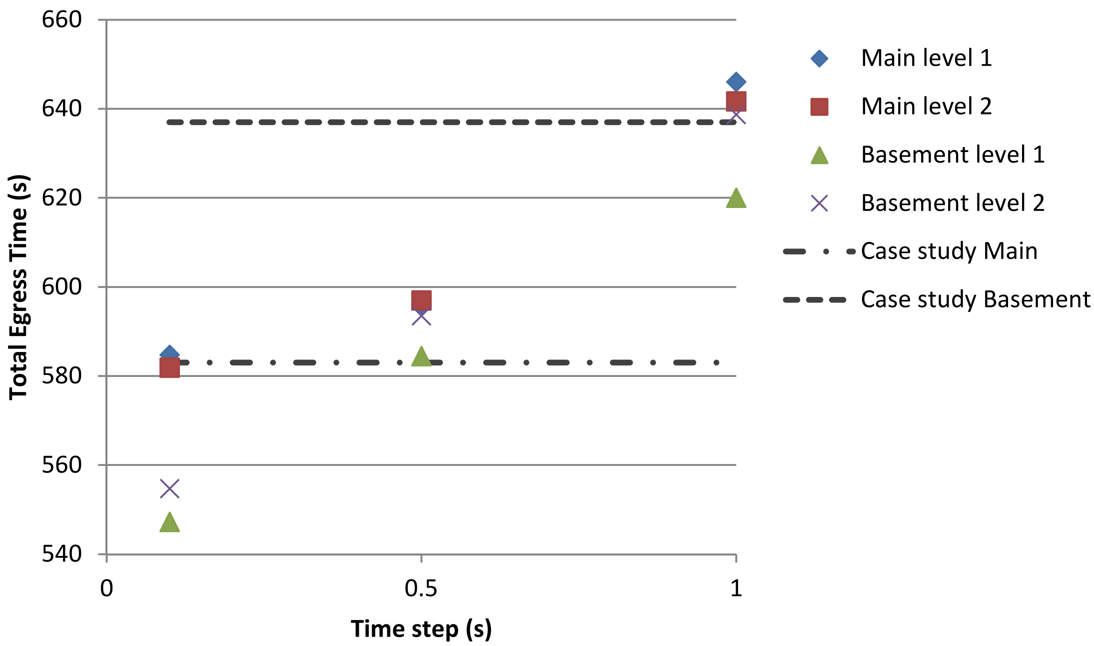

Figure 22: Majestic Building Simulated Egress Time for a Range of Time Steps

The changes in total evacuation time for the Majestic building decreases with each reduction in time step. The time decrease as a percentage is between 7 to 9% going from 1 s to 0.5 s across the three levels of simulation. A smaller decrease of 2 to 4% occurs when further reducing the time step from 0.5 s to 0.1 s.

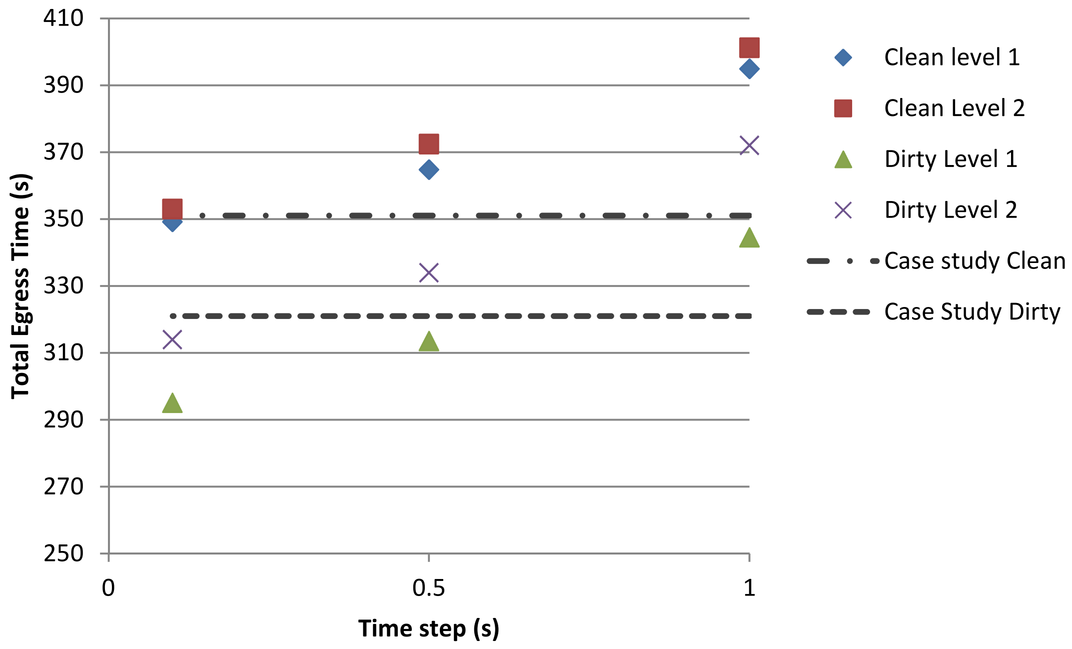

Figure 23: Manchester Building Simulated Egress Time for a Range of Time Steps

Time step reduction has a similar effect on total evacuation times for the Manchester building, while only tested across two levels. A reduction of time step from 1 s to 0.5 s decreases the total evacuation time as a percentage approximately 7 to 10% across the levels simulated. Again, a smaller of decrease of 4 to 6% occurs when the time step is reduced from 0.5 s to 0.1 s.

In terms of computational requirements, for the four stairs analysed; 1 s time steps take on average 5 s computational time per simulation; 0.5 s time steps take on average 12 s and 0.1 s time steps take on average 75 s per simulation.

4.2.2 Tread and Riser

Equation 1 from Gwynne and Rosenbaum (2008) for speed of occupants is modified by a factor k, as discussed in Chapter 3. Gwynne and Rosenbaum stated that this varies approximately linearly as a function of the square root of the ratio of tread to riser. ENZ uses this relationship as an equation for k shown below in Equation 3.

$$k = \sqrt{\frac{\text{tread}}{\text{riser}}} \qquad \text{(Equation 3)}$$

The Majestic building stair risers of 150 mm (260 mm tread) are less than the typical values found in Table 5. While the Manchester building stair treads of 245 mm (190 mm riser) are less than the typical tread values. Gwynne and Rosenbaum state that there is no validation for the above equation outside of the typical values provided.

The tread and riser analysis assesses the cases where building stair configurations are outside the typical configurations provided in Table 5. This confirms that the change in speed using total egress times as a measure is appropriate for the magnitude of change in k.

The tread and riser analysis confirms that the buildings with tread and/or riser dimensions outside the values provided by Gwynne and Rosenbaum are performing with extrapolated k factors reasonably. Comparison is made to the same modelled stairs using the nearest typical stair dimensions. The two stairs with non-typical stair configurations were Manchester Clean stair: 190 mm riser, 245 mm tread; and Majestic Main stair: 150 mm riser, 260 mm tread. The nearest typical configurations were 190 mm riser, 254 mm tread and 165 mm riser, 254 mm tread. These ratios are within the range given by Gwynne and Rosenbaum (2008).

Results of the analysis are presented in Table 7 below, 50 simulations were run for each case and the average was calculated. The change between the typical configuration and the actual case study configuration is shown as a percentage.

Table 7: Comparison for Manchester and Majestic Stair Tread and Riser Configurations

	Typical Stair Configuration	Actual Stair Configuration
Manchester Clean	374 s	364 s
Percent change	-1.6%	
Majestic Main	620 s	596 s
Percent change	4.1%	

The change in both stairs' time is what is expected for the magnitude of change in stair configuration. Using Equation 3, a decrease in tread size of 10 mm for the Manchester clean stair should increase speeds in the range of 1 to 2%. While a change of approximately 25 mm to the riser dimension, for the Majestic Main stair should reduce speeds by approximately 4 to 6%.

Therefore the EvacuatioNZ equation based extrapolation is working sufficiently. However, these stairs might be considered a minor variation to the provided values by Gwynne and Rosenbaum as only one measurement was outside the provided range, and the dimensional variation was less than 5%.

4.2.3 Geometric Variable

How the node network is set up to represent the building space for a multi-storey building can affect the simulation performance as discussed by Tsai (2007). Understanding the impact of different layouts will provide recommendations for future use of EvacuatioNZ.

Three types of node layouts for the stairs were investigated beginning with a simple layout following Tsai's suggestion (2007), and two versions of more complicated node layouts.

1. Simple layout – stair flight and landing are represented by a single node

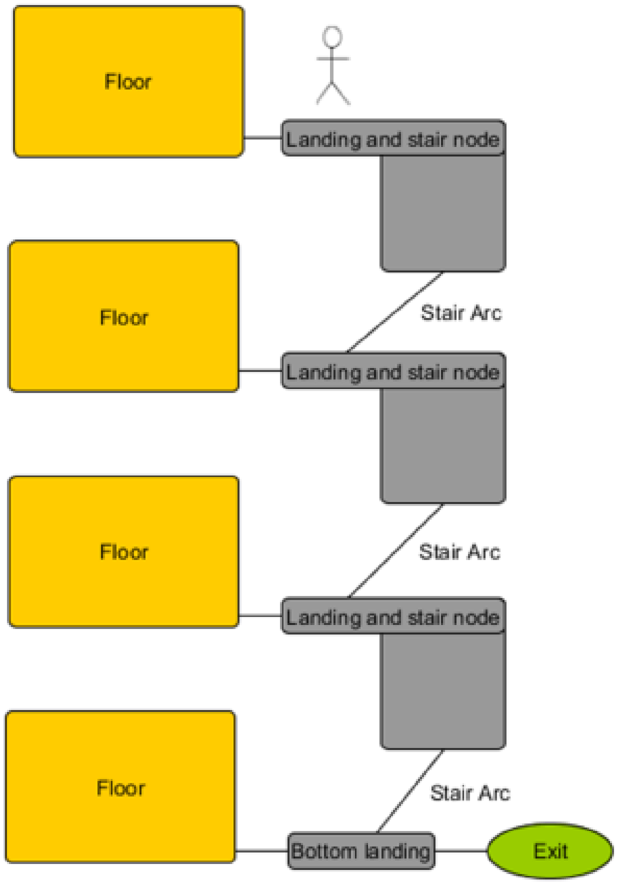

Figure 24: Simple yEd Node Network Layout for Stairs

Figure 24 shows three flights of stairs as represented in yEd using the simple layout. Landing nodes represent the stairwell, including all landings between floors and the stair flight area. The connector is specified for the whole length, including landing distance, as a stair movement constriction.

2. Complex layout type A – the landing, or both landings in case of mid landing stairs, is represented by a single node. The stair flights are represented by a separate node

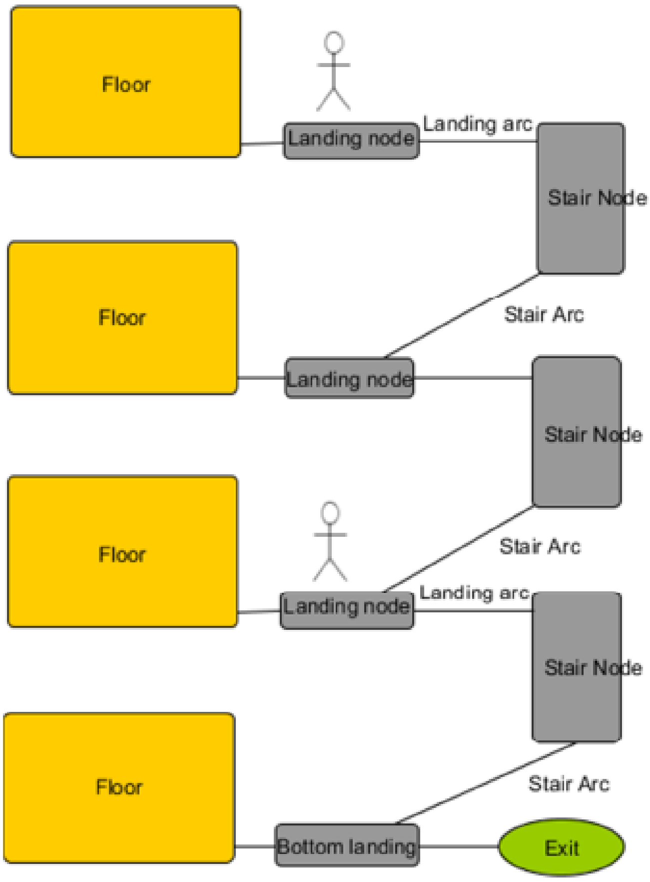

Figure 25: Complex Type A yEd Node Network Layout for Stairs

Figure 25 is a stair type A complex layout. This layout is still an abstract representation of stairs with mid-flight landings, but a reasonably true representation of single flight stairs such as scissor stairs.

In this layout, the landing node has the dimensions of the combined area of all the landings in the stair. The connection from landing to stair is then a default path constriction. The stair nodes represent the stair flight standing space. The connection is specified as the sum of all the stair flight lengths, as a stair movement constriction.

3. Complex layout type B – each landing and stair flight is represented by an individual node

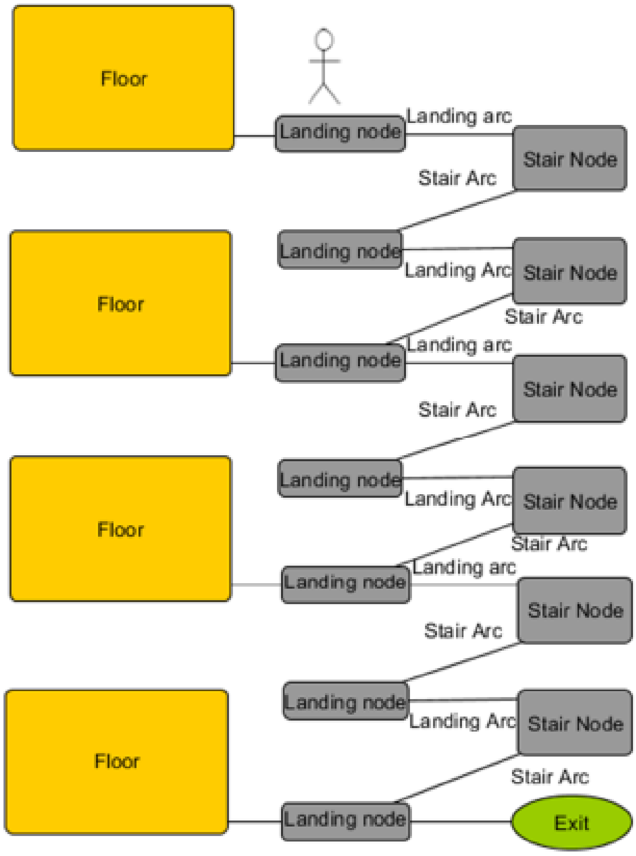

Figure 26: Complex Type B yEd Node Network Layout for Stairs

Figure 26 is a stair type B complex layout. This layout increases complexity by using nodes for the mid-floor landings. This layout is a reasonably true representation for half-turn/dogleg type stairs. It is assumed to represent square shaped spiral staircases as well, due to the model not accounting for turning, making the two types of stairs modelled similarly.

4.2.4 Agent Input Variation Types

This research focuses on the differences in egress times between computer model agents and the case study occupants. The sensitivity of occupant variables analyses the impact on the results dependent on how the starting conditions of the agents are specified. There are two primary variables for the agents which were assessed;

1. Stair entry time
2. Starting floor populations

These two factors were varied in three types of analyses using gross data taken from the case study results and used as the basis for distributions. See Chapter 2 for further detail on case study data processing.

- Variation Type One (V1)

A base case where agents were not matched to the case study data; instead they were randomly assigned a starting floor and stair entry time. The total population was ensured to be equal to the case study. Stair entry times are randomly selected from a normal distribution derived from the case study entry times.

- Variation Type Two (V2)

This case varies matches the starting floor populations to the case study exactly. Stair entry is still randomly selected from the derived normal distributions.

- Variation Type Three (V3)

This model matches the case study data exactly, assigning starting floor and stair entry time to each agent.

The geometric and occupant variable analysis was carried with a time step of 0.5 s. Simulations were carried out until 0.05% convergence was achieved; the resulting converged averages are presented in Table 8 to Table 11.

Table 8: Majestic Main Stair Layout and Occupant Variable Sensitivity

	Simple Layout			Complex A Layout			Complex B Layout		
Agent Variation Type	1	2	3	1	2	3	1	2	3
Average (s)	563 ± 19	550 ± 17	615 ± 36	569 ±15	560 ± 15	548 ± 12	672 ± 20	663 ±20	645 ± 21
Error vs. case study (%)	-3.4	-5.6	5.5	-2.5	-3.9	-6.1	15.2	13.7	10.6

Table 9: Majestic Basement Stair Layout and Occupant Variable Sensitivity

	Simple Layout			Complex A Layout			Complex B Layout		
Agent Variation Type	1	2	3	1	2	3	1	2	3
Average (s)	500 ± 23	537 ± 11	538 ± 8	519 ± 11	544 ± 10	540 ± 8	587 ± 15	600 ± 12	598 ± 15
Error vs. case study (%)	-21.5	-15.6	-15.5	-18.5	-14.6	-15.2	-7.8	-5.8	-6.1

Standard deviations on the model results were small relative to the total egress time, ranging from ±8 to ±23 s.

There are trends for both stair layout and agent variation types. In both the Main stair (Table 8) and the Basement stair (Table 9), changing from a simple layout to the complex A layout increased egress times. Changing from complex A to complex B increased egress times significantly. Complex B layout egress times were also larger than the simple layout.

Changing agent variation type decreased the egress time for the Main stair in all layouts, and increased egress time for the Basement stair in all layouts. However, the change from V2 to V3 was not more than 3% in all cases except for the simple layout of the Main stair, where the change was 10%.

The Main stair complex B layout achieved a difference of less than 15% to the case study times, with all the times being on the conservative side. The Basement stair complex B layout achieved the closest results to the case study times, of which all the results were non-conservative.

Further comparison was carried out using min-max cumulative charts for the two complex layout types. These plots are used to compare the exit flow rates, which give an indication of stair descent performance of the simulated agents compared to case study cumulative evacuation data.

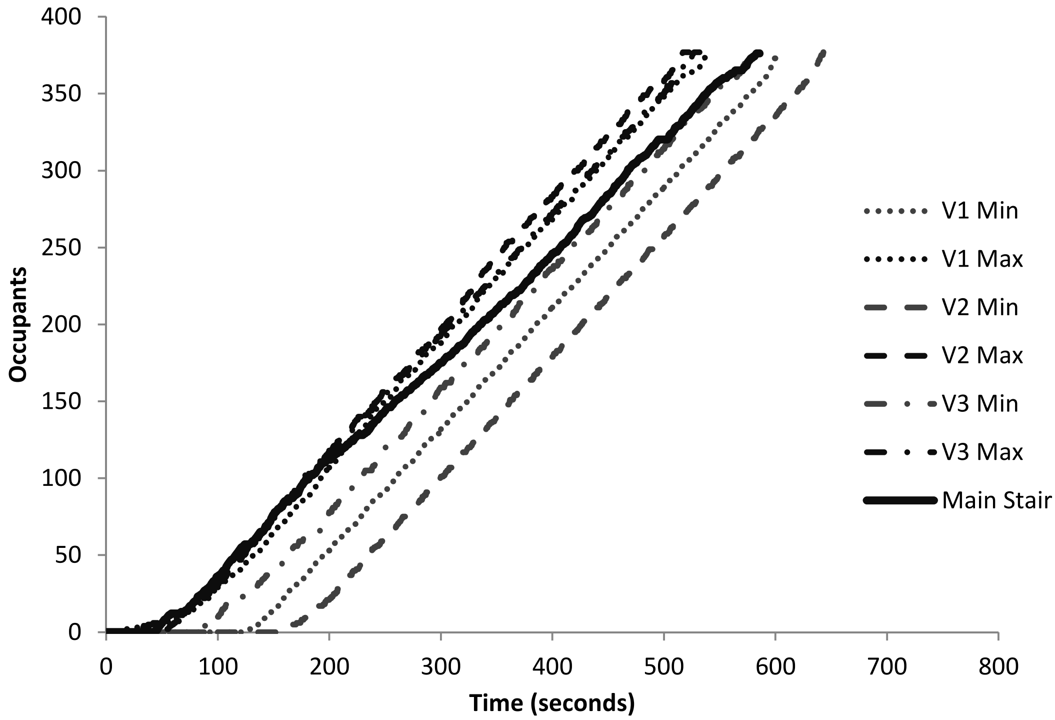

Figure 27: Majestic Main Stair Complex A Layout Comparison

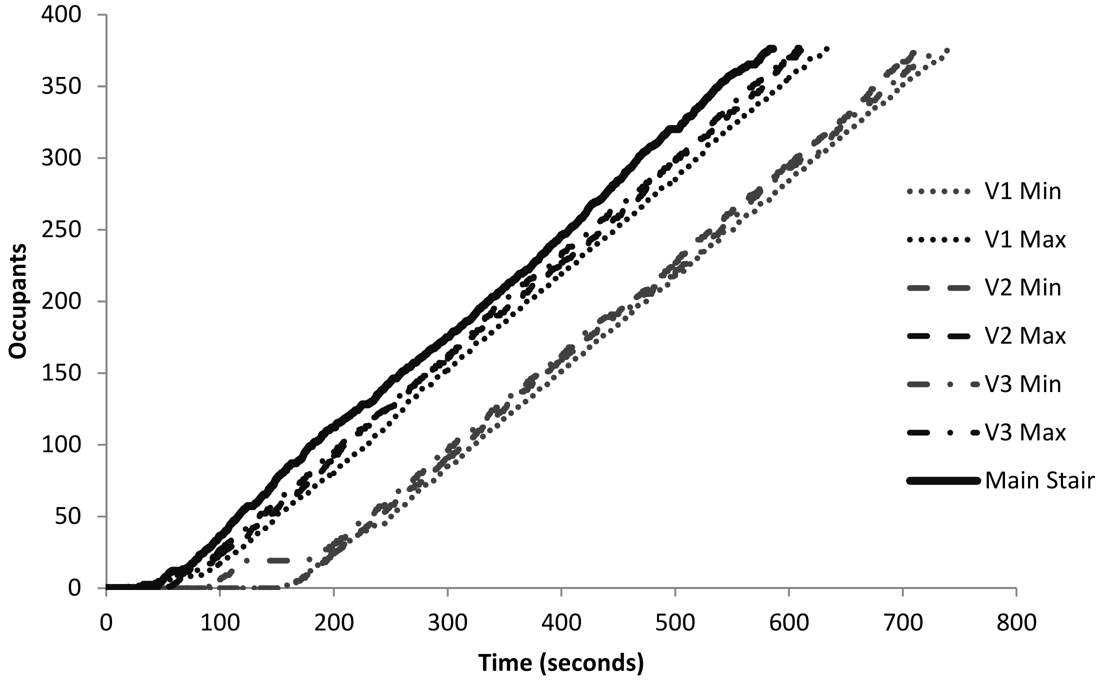

Figure 28: Majestic Main Stair Complex B Layout Comparison

Relative to the approximate case study gradient of 0.67 people/s, the complex type A layout (Figure 27) has a steeper gradient for all agent variation types ranging from 0.73 to 0.83 people/s. This indicates a faster descent for the agents. The complex B layout (Figure 28) has a range of 0.62 – 0.65 people/s which is similar to the case study. The difference in total egress time compared to the case study data for the complex B layout is due to differences in stair entry times.

For both layouts, all the variation types have very similar flow rates. A large difference between V3 and V2 in terms of first stair entry time seems to have no impact on the V3 line converging and then following a similar path to V1 and V2 lines.

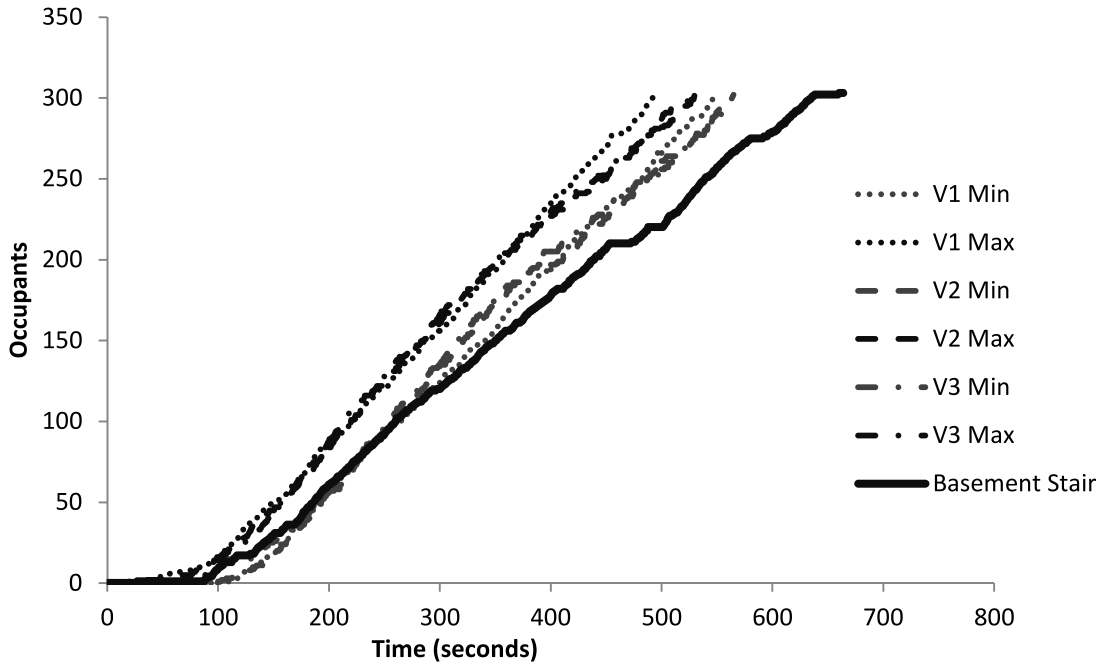

Figure 29: Majestic Basement Stair Complex A Layout Comparison

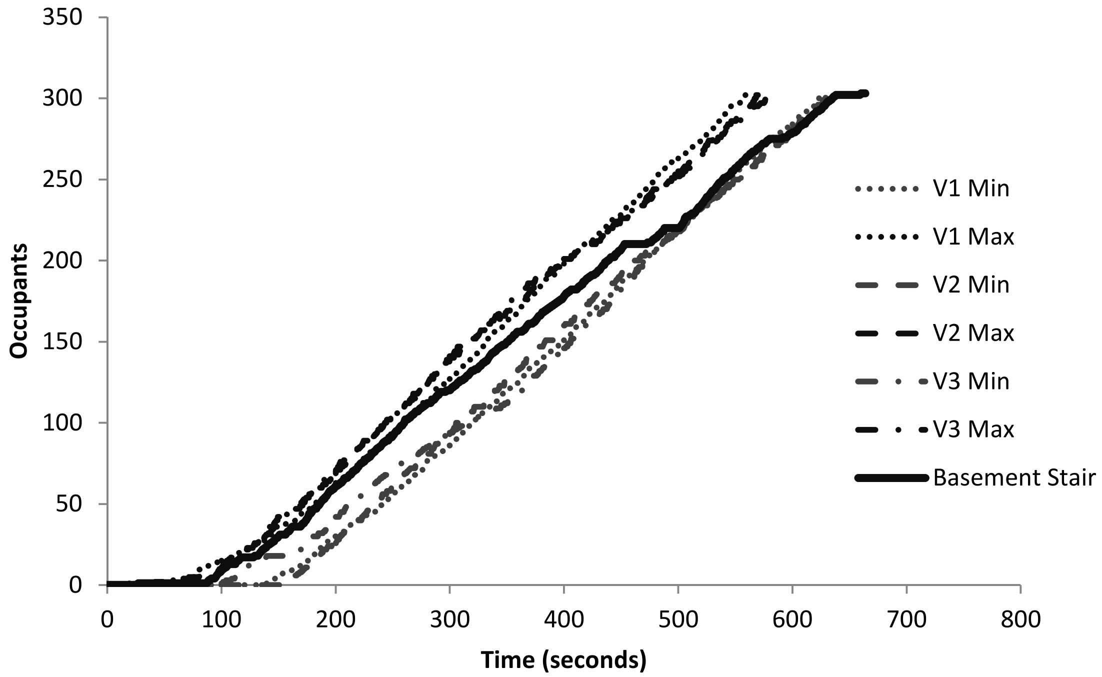

Figure 30: Majestic Basement Stair Complex B Layout Comparison

The Basement stair case study had a flow rate of approximately 0.59 people/s. The complex A layout (Figure 29) has a flow rate range of approximately 0.67 to 0.74 people/s. The complex B layout (Figure 30) has a flow rate for all occupant variations of approximately 0.61 people/s. The difference in total egress time appears primarily due to a short slow down in the case study data around 480 s into the evacuation.

For both layouts, all the variation types have very similar flow rates. A large difference between V3 and V2 in terms of first stair entry time seems to have no impact on the V3 line converging and then following a similar path to V1 and V2.

The difference in results for agent variation type was not significant, as discussed above. The difference between min and max results are smaller, being around 5%. In Figure 27, and clearer in Figure 31 and Figure 32, despite a large difference of time for the first occupant beginning to egress, the lines for V1, V2 and V3 converge and end close together (within 10%).

Table 10: Manchester Clean Stair Layout and Occupant Variable Sensitivity

	Simple Layout			Complex A Layout			Complex B Layout		
Agent Variation Type	1	2	3	1	2	3	1	2	3
Average (s)	367 ± 16	376 ± 11	392 ± 8	361 ± 10	374 ± 15	381 ± 9	442 ± 13	455 ± 12	455 ± 12
Difference to case study (%)	4.7	7.3	11.7	2.7	6.7	8.5	26	29.5	29.7

Table 11: Manchester Dirty Stair Layout and Occupant Variable Sensitivity

	Simple Layout			Complex A Layout			Complex B Layout		
Agent Variation Type	1	2	3	1	2	3	1	2	3
Average (s)	258 ± 10	268 ±7	296 ± 4	312 ± 21	329 ± 21	371 ± 12	479 ± 18	512 ± 15	523 ± 10
Difference to case study (%)	-19.6	-16.5	-7.8	-2.9	2.5	15.6	49.3	59.6	62.8

Standard deviations on the model results were small relative to the total egress time, ranging from ±8 to ±21 s.

There are similar trends for both stair layout and agent variation types for the Manchester Stairs as is found for the Majestic stairs. For the Clean stair (Table 10), changing from simple to complex A decreased egress times. In the dirty stair (Table 11) however, this increased egress times. Changing from complex A to complex B increased egress times. Complex B layout egress times were longer than the simple layout in both stairs.

Changing the agent variation type increased the egress times for both stairs in all layouts. Again, the changes from V2 to V3 were smaller than from V1 to V2, typically not more than 3%.

In both stairs, the complex A layout achieved the smallest difference in egress times to the case study times. The complex B layout had the largest difference to the case study times, but was on the conservative side.

As with the Majestic stairs, further comparison was carried out using min-max cumulative charts for the two complex layouts. Note that the tail end (after ~350 s) for the Clean stair case study time was excluded for the total egress time comparisons.

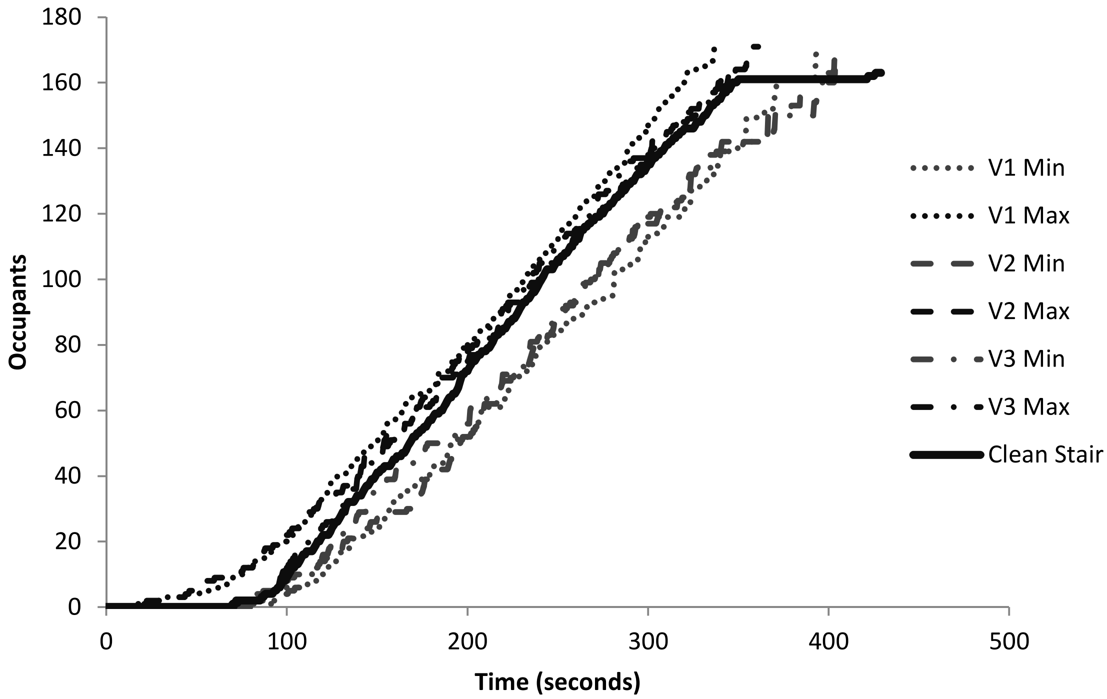

Figure 31: Manchester Clean Stair Complex A Layout Comparison

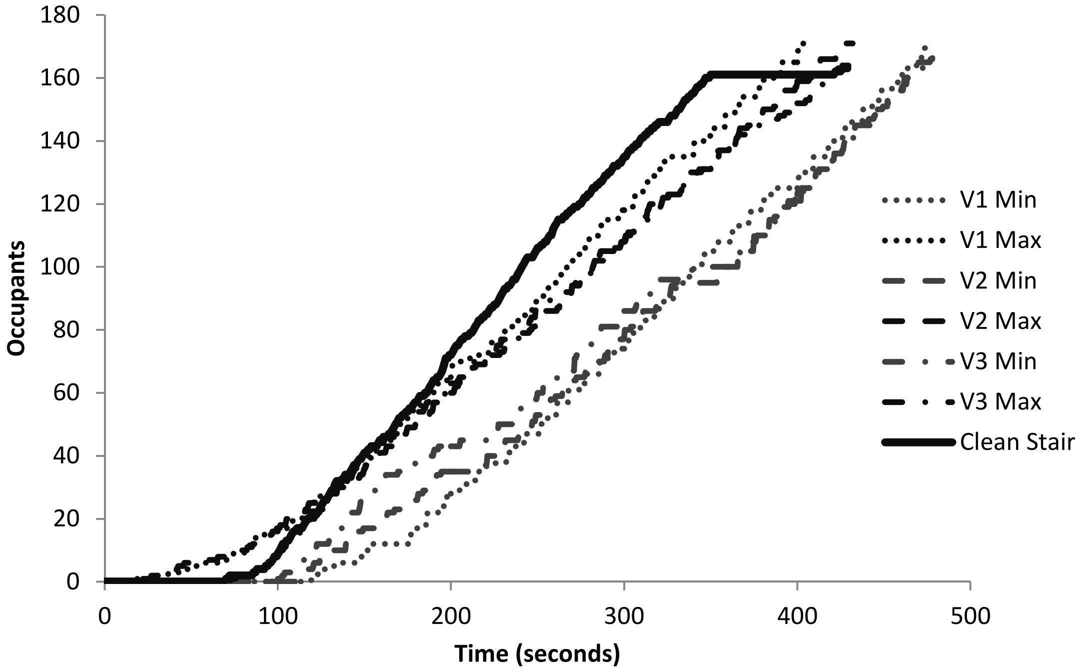

Figure 32: Manchester Clean Stair Complex B Layout Comparison

The case study descent rate is approximately 0.61 people/s. The complex type A layout (Figure 31) has an estimated gradient of 0.59 people/s for all occupant variations. The complex B layout (Figure 32) has a slower flow rate of 0.47 people/s and 0.59 people/s. This layout also had a few periods of little or no exit flow, which does not occur in the case study data.

For both layouts, all the variation types have very similar flow rates. Despite the first stair entry times for the 'min' agent variation types being significantly different the three eventually converge and follow a similar path. The 'max' lines have very similar stair entry times and follow a similar path with the exception of the V3 line which appears to experience an additional slow down late in the evacuation, around 300 s.

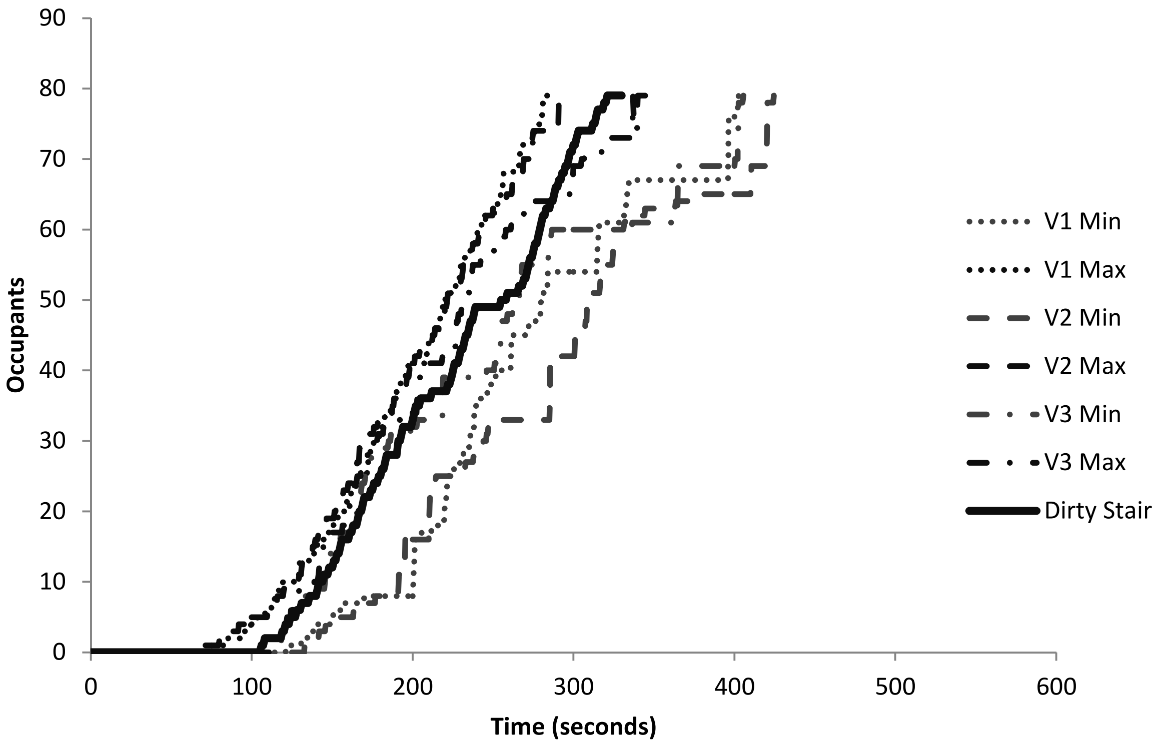

Figure 33: Manchester Dirty Stair Complex A Layout Comparison

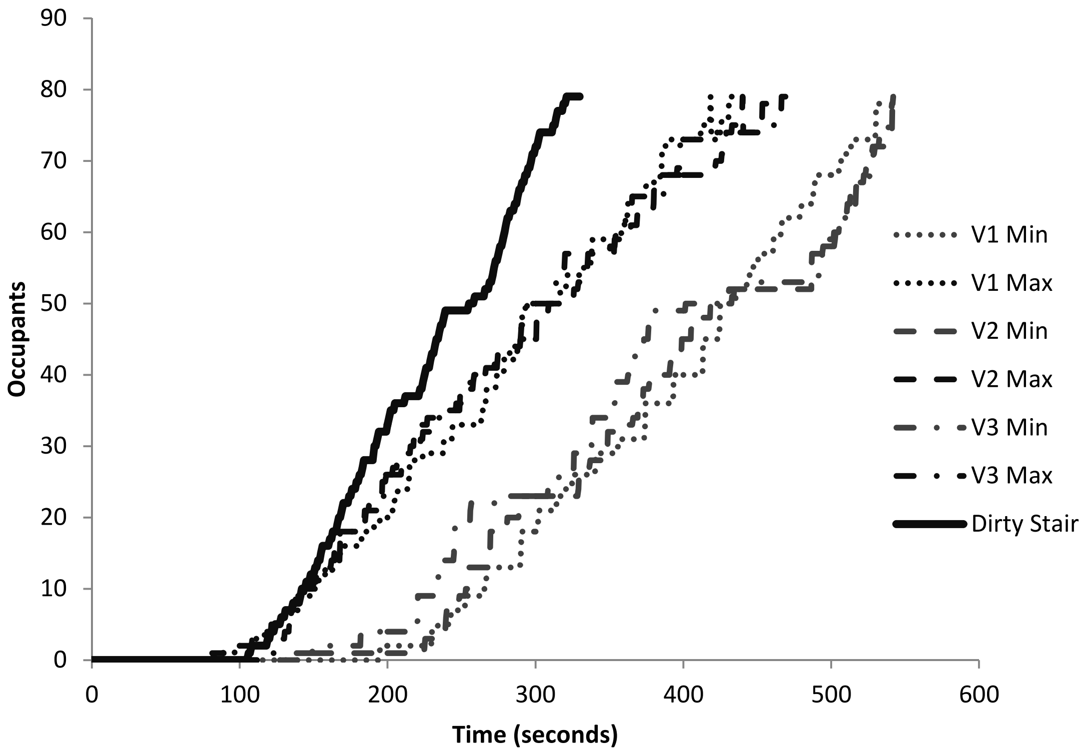

Figure 34: Manchester Dirty Stair Complex B Layout Comparison

The Dirty stair case study had an average estimated flow rate of 0.37 people/s. The complex type A layout (Figure 33) has a similar gradient ranging from an average 0.33 to 0.49 people/s. The complex B layout (Figure 34) has a shallower average gradient of 0.22 people/s for most occupant variation types.

The 'max' lines for the complex A layout and all the lines of the complex B layout have significant staggering. This shows time periods of little to no exit flow rate. Both layouts demonstrate greater amounts of staggering than the case study.

Agent variation type 1 and 2 follow similar paths in the complex A layout. In the complex B layout all three variation types have similar paths. First stair entry times in both layouts are close together for all variation types.

4.3 Sensitivity Conclusions

Based on the results found in the sensitivity analysis found the following conditions are determined to be best fit for model results to compare to the case study data;

1. Time step of 0.5 seconds

   A decrease in time steps decreased total egress times, indicating there was a rounding artefact within the model. A time step of 0.5 s was selected over 0.1 s to reduce this artefact. This selection was based on the change to egress times from 0.5 s to 0.1 s being half as much as the change from 1.0 s to 0.5 s. Additionally, the computational effort for each simulation increased by 600% for a 0.1 s time step compared to 1.0 s.

2. No adjustment for tread and risers with minor variation to the provided range

   The sensitivity found the change in egress times to match that of the change to agent speed for the tread to riser ratio of values outside those provided by Gwynne and Rosenbaum. Therefore, using k calculated from tread and riser dimensions with minor variations (less than 20 mm) to the range found in Table 4 is appropriate.

3. A complex B layout for stairs which have mid-flight landings and complex A layout for stairs without a landing

   Analysis found the flow rates for the complex B layout approximated the case study data well in both the Majestic building stairs. Whereas the complex A layout produced faster flow rates. However, in the Manchester building the complex A layout had a close flow rate for the Clean stair and a slightly faster flow rate for the Dirty stair. While the complex B layout produced flow rates slower than the case study data.

   The complex B layout is selected as most appropriate for further modelling due to being similar to or slower (more conservative) than the case study data, where the complex A layout is often faster and therefore less conservative. The complex B layout is the closest modelling approximation of a dog-leg type stair or stairs with one mid-landing between floors.

4. Agent input variation type 2; assigned starting floors and random stair entry time inputs from a distribution based on case study data

   The total egress tables found the changes from V1 to V2 were typically less than 5% and changed the result closer to the case study in half of the results. Changes from V2 to V3 typically had changes less than 3% or no change at all and changed the result closer to the case study in half of the results.

   The cumulative charts showed that V3 generally had first stair entry times closer to the case study and were significantly different to the other two variation types. However, all three lines typically converged and had similar gradients after that.

   Therefore, V2 was selected on the basis of requiring less detailed data than the V3 input while producing similar results. V2 was also more consistent than the V1 results.

5 Modelling Results

The relevant results from the EvacuatioNZ simulations are summarised in this Chapter. Data from the results are presented in three different forms for comparison to the case study data.

All simulations were carried out with a time step of 0.5 seconds, convergence criteria of 0.05% and with a type 2 agent input variation (V2). The Manchester, Majestic and Unisys buildings were all modelled with a complex type B layout to represent the mid-flight landings. The Christchurch building was modelled with the complex type A layout as these two stairs did not have a mid-flight landing.

The three types of outputs are;

1. The total evacuation time presented as an average and with standard deviations in seconds, represents the time taken for the last occupant to reach a safe node.

   This type of comparison is quick and simple to make and gives coarse indication of the relative performance of the model against the case study data. The standard deviation gives the variability of the results which relates to the variability of the inputs. However, the single number nature of the result can be misleading when the model results or the data that is being compared to have outliers.

2. The min-max cumulative diagrams show the cumulative evacuation of occupants from the building. The top and bottom line represent the minimum and maximum results respectively, from the whole series of simulations.

   This comparison is more detailed, giving information about the egress flow. This can be used as an indicator of the descent performance. The cumulative plot also show up occupants or agents which have a very long pre-evacuation time, which would result in a larger total egress time than might be achieved otherwise.

The minimum and maximum output of this comparison brackets the range of results given by the model, allowing the user to look at best or worst performances for the distribution of inputs used.

3. Descent charts are a suggested means to present results by Pauls (2003) for multi-storey evacuations. These diagrams show individual descent as they reach each floor landing down the building as a function of time. Individuals for the descent charts were sampled to be displayed based on two criteria;

   - Two simulations were chosen per stair, based on the longest and shortest total egress times

   - For each simulation, from the uppermost populated floor, the occupant/agent with the minimum and maximum stair entry times for that floor were chosen

Occupants and agents are sampled from the uppermost floor, as this floor has the occupant with the longest egress time for most of the case study buildings. The exception is the Majestic Basement, where the 25th level occupant as opposed to the uppermost 27th level had the longest egress time. The sample is taken from level 25 for the Majestic Basement case study for this reason.

Descent charts are a detailed representation of an individual descending the stair; given the data has enough points to show the majority of the path. This type of comparison can compare differences between the model and the case study, particularly when the data has specific events within the stairwell that can change the eventual egress time from a linear result.

However, descent charts are time consuming to create from the set of data and the nature of sampling can miss information about other occupants. These occupants may be influencing the evacuation in a way not shown with the occupants sampled.

5.1 Total Egress Time

Total egress time for all four study buildings are summarised in Figure 35. The model results are presented as the converged average egress time with a standard deviation. Throughout the results, there does not appear to be a link between number of simulations for convergence and the end result for a given stair model.

Figure 35 summarises the model results for all four buildings compared to the case study results. The model simulations are generally close to the case study results, three are longer, two are shorter and three are within 5% of the case study data. Two of the three close results are shorter times. Half the results were conservative and half were not. Manchester had the highest percentage difference to the case study by a significant margin. All the other results were within ±15% of the case study data, with an average difference of 8.6%

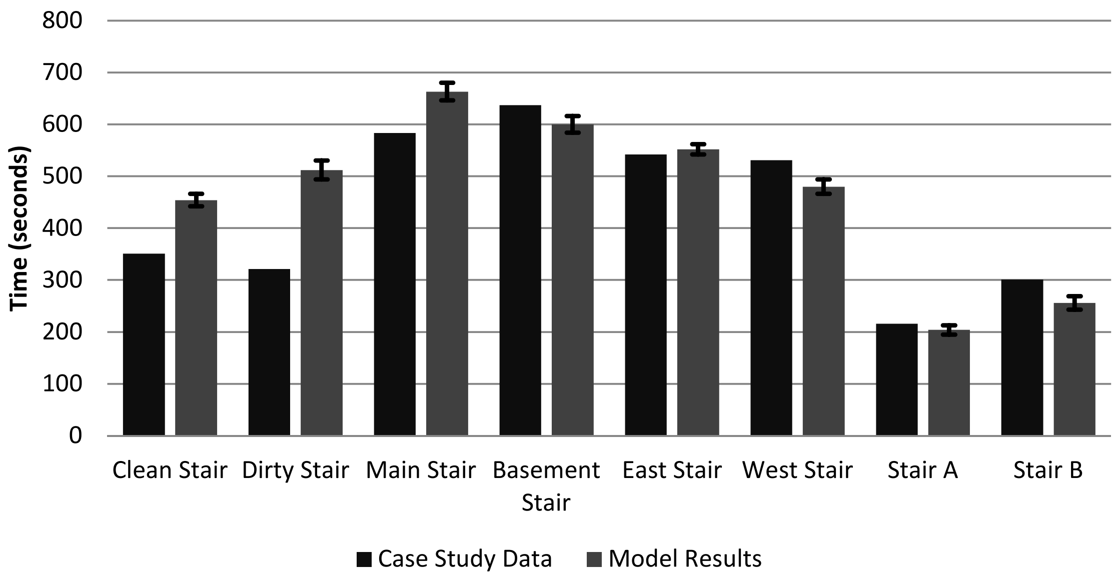

Figure 35: Bar Chart Summary of Total Egress Time for ENZ Model Compared to Case Study Results

Detailed comparison for each building is shown in the following Tables (12 to 15) which present the converged total egress time with standard deviation along with the number of simulations required for the 0.05% convergence and percentage difference comparison to the case study times.

5.1.1 Manchester Stair Model Total Egress

As discussed in 4.1.1 and described in Chapter 2, Manchester Clean stair's total egress time of 351 seconds is an adjusted value.

Table 12: Manchester Total Egress Time Model Results

	Clean stair	Dirty stair
Time (s)	454 ± 12	512 ± 18
Simulations	120	157
Case study time (s)	351	321
Difference (%)	30	59

The model achieves a predicted result for the Clean stair (Table 12) with a difference of 30% to the case study with a variation of ~2.6%. For the Dirty stair the result was 59% different to the case study with a variation of ~3.5%. Convergence required over a 100 simulations for both stairs.

5.1.2 Majestic Stair Model Total Egress

Table 13: Majestic Total Egress Time Model Results

	Main Star	Basement Stair
Time (s)	663 ± 17	600 ± 16
Simulations	21	47
Case study time (s)	583	637
Difference (%)	13.7	-5.8

The model achieves a predicted result for the Main stair (Table 13) with a difference of 13.7% to the case study with a variation of ~2.5%. The Basement stair the result was within 6%, but non-conservative of the case study with a variation of ~2.7%. Convergence required less than 50 simulations for both stairs.

5.1.3 Unisys Stair Model Total Egress

Table 14: Unisys Total Egress Time Model Results

	East Stair	West Stair
Time (s)	480 ± 10	552 ± 14
Simulations	90	41
Case study time (s)	542	531
Difference (%)	-12	4.0

The East stair model prediction was 12% different to the case study result and non-conservative, with a variation of ~2.1%. The West stair model result has a difference of 4% to the case study with a variation of ~2.5%. Convergence required 90 simulations for the East stair and 41 for the West stair.

5.1.4 Christchurch Stair Model Total Egress

Table 15: Christchurch Total Egress Time Model Results

	Stair A	Stair B
Time (s)	204 ± 9	256 ± 13
Simulations	177	95
Case study time (s)	216	301
Difference (%)	-5.5	-14.9

The model achieves a predicted result for Stair A with a difference of 5.5% to the case study with a variation of ~4.3%. For Stair B the result was around

14.9% of the case study with a variation of ~5%. Both results were non-conservative. Convergence required 177 simulations for Stair A, while stair B required less than 100 simulations

5.2 Min-max Cumulative Charts

The results of estimated average egress flow rates from the min-max cumulative charts evacuation is summarised in Table 16. Many of the model flow rates were close (within 10%) to the case study flow rates. Three stair models were not this close to the case study result, Manchester Dirty stair being 37% slower, Majestic Basement stair being 17% faster and Christchurch stair B being 57% faster. However, the Christchurch B stair model had a very similar average flow rate to the case study (2% difference) for the first 100 seconds. Also, first stair entry times for the model were close to, or included the case study first stair entry time within the range of results.

Table 16: Summary Table of ENZ Model Cumulative Evacuation Egress Flow Rate Results Compared to Case Study Results

Building	Stair	Average Case Study Egress Flow Rate (people/s)	Average Model Egress Flow Rate (people/s)
Manchester	Clean	0.61	0.46 – 0.57
	Dirty	0.37	0.23
Majestic	Main	0.70	0.69
	Basement	0.56	0.62 – 0.66
Unisys	East	0.62	0.68
	West	0.65	0.70
Christchurch	A	0.62	0.63 – 0.68
	B	0.75 - 0.49	0.65 – 0.77

5.2.1 Typical Cumulative Chart

An example of a typical cumulative chart is shown for Majestic Main Stair (Figure 36), with the cumulative total number of people who have exited the stair are on the y-axis and the time in seconds is along the x-axis. The case study result is represented by a solid black line and the model results are shown with dotted lines. Cumulative charts for other stairs can be found in Appendix III.

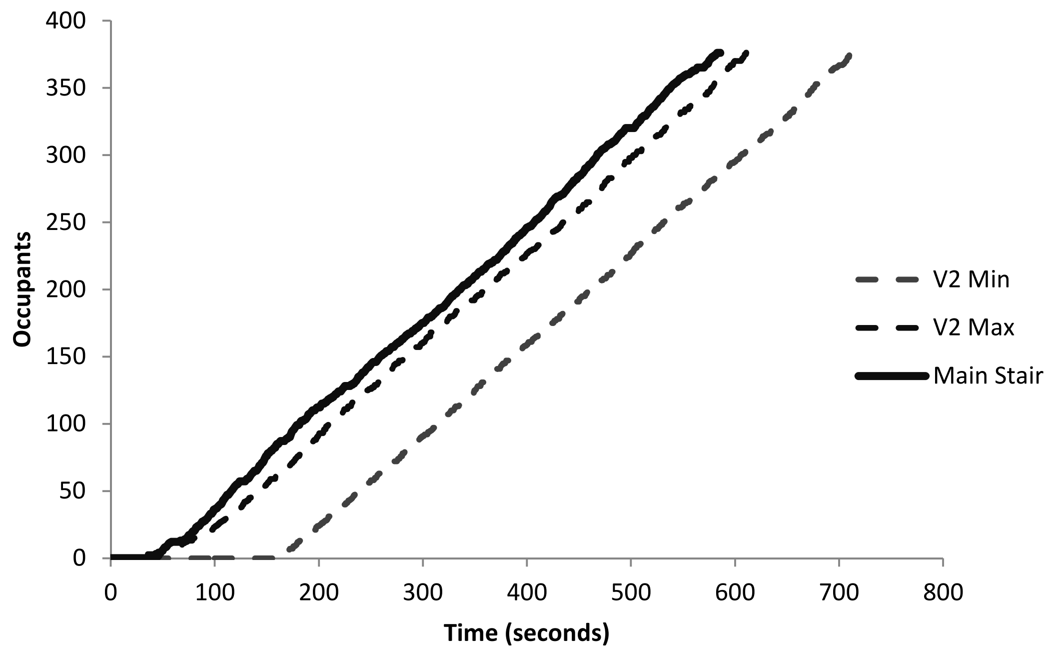

Figure 36: Majestic Main Stair min-max Cumulative Plot Comparison with Case Study Results

The range of results from the Majestic Main stair model is near to the case study on the conservative side (Figure 36). The average egress flow rate for the case study was estimated to be 0.7 people/s. The model flow rates were both approximately 0.69 people/s. Egress flow rate for model and case study were consistent throughout the evacuation.

5.3 Individual Descent Charts

The results for average descent speed for sampled individuals from the individual descent charts is summarised in Table 17. On average, model agents have similar or slower descent speeds than the sampled case study occupants. Only the basement stair has faster speeds, and in that case the difference is 0.05 m/s. The largest difference in speed was 0.35 m/s, for Christchurch building stair B.

Total egress times of the sampled model agents are on average similar (less than 30s) or longer than the case study data. In most of these cases the stair entry times are also similar. The one case with the model agents having generally shorter egress times is Christchurch A where the model agents also had shorter stair entry times.

Descent speeds are estimated from the gradients of the lines, which gives the number of floors per metre as a descent rate. This was multiplied by the total travel distance estimated in Table 6 to give a descent speed in metres/second.

Table 17: Summary Table of ENZ Model Individual Descent Speed Results Compared to Case Study Results

Building	Stair	Average Case Study Descent Speed (m/s)	Average Model Descent Speed (m/s)
Manchester	Clean	0.64 – 0.68	0.45 – 0.61
	Dirty	0.39 – 0.71	0.33 – 0.43 (0.62)
Majestic	Main	0.41 – 0.63	0.31 - 0.58
	Basement	0.63	0.68
Unisys	East	0.38 – 0.42	0.36 – 0.41 (0.67)
	West	0.45 -0.47	0.26 - 0.43
Christchurch	A	0.49 – 1.27	0.41 – 0.94
	B	0.22 – 0.90	0.20 – 0.55

5.3.1 Typical Descent Chart

An example of a typical individual descent chart is shown for Christchurch Stair A (Figure 37) and a stair of interest was Unisys West Stair (Figure 38). The floor number is on the y-axis and the time in seconds is along the x-axis. The case study occupants are represented by a solid black line, the model agents are shown with dotted grey lines representing the agents from the shortest model simulation, and the dashed grey lines representing the agents from the longest model simulation. The full set of individual descent charts can be found in Appendix III.

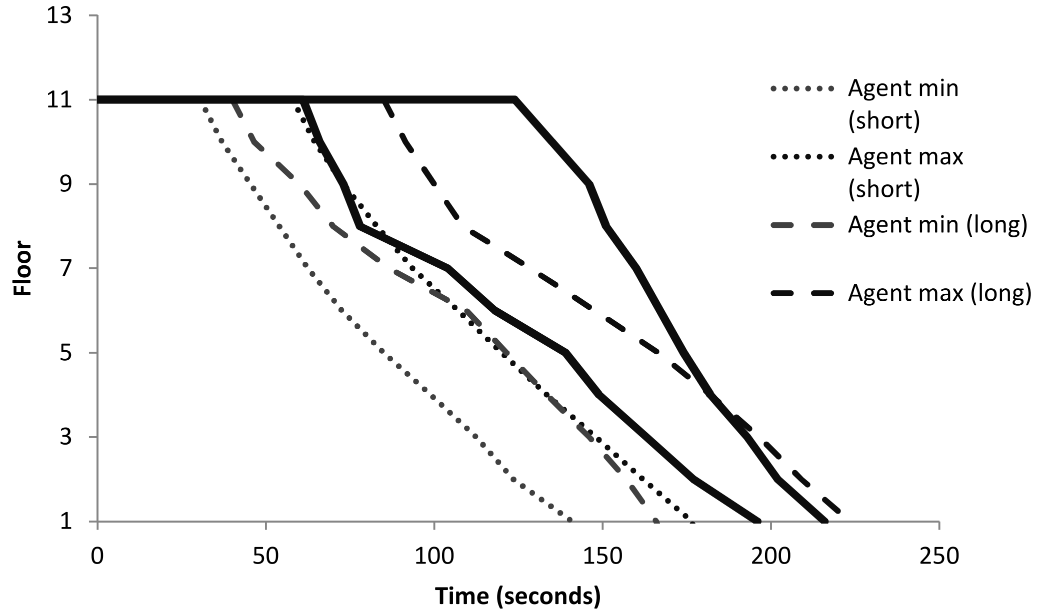

Figure 37: Christchurch Stair A Descent Plot with Comparison to Case Study Occupants

The model agents have stair entry times shorter than the case study occupants sampled (Figure 37). The case study occupant's speed is estimated to be 1.27 m/s at the fastest, the minimum occupant slowed down to 0.49 m/s after floor 8. The agents from the short simulation had average speeds of approximately 0.6 m/s. Some agents had faster estimated speed of 0.94 m/s, which slows to 0.41 m/s around floor 8.

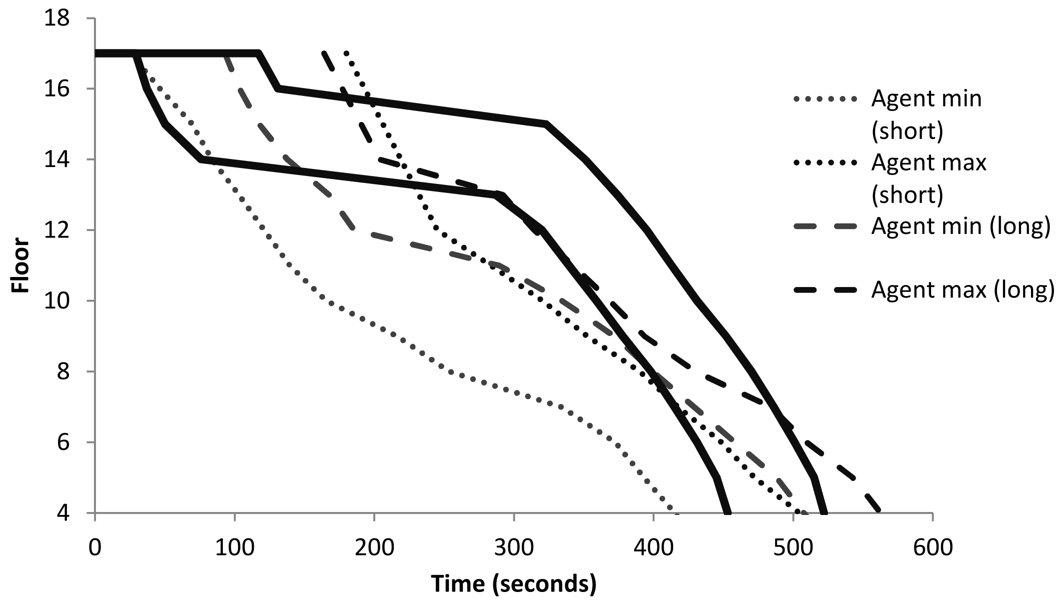

Figure 38: Unisys West Stair Descent Plot with Comparison to Case Study Occupants

The sampled occupants for the Unisys West stair experience significant delay around floor 14 for the minimum occupant and floor 16 for the maximum occupant. Some of the model agents experience a similar event, particularly from the long simulation. The short simulation agents do not experience as much delay.

6 Hand Calculation Method

Following on from the modelling of the case study buildings using ENZ, a comparison is carried out against a simple hand calculation method. This comparison between case study, computer model and hand calculation provides further information on differences between design methods and indicate potential changes in modern occupant's egress performance.

The simple hand calculation will be Paul's simplified method for multi-storey buildings based on his research in the 70's and 80's.

6.1 Simplified Hand Calculation Equation

In a paper published in 1987, Paul's presented a simplified calculation to predict the total evacuation time for multi-storey buildings between 8-21 stories high. This method was included in the SFPE handbook but has since been withdrawn from the 4th edition.

Paul's observed trial evacuations from a range of buildings and collated the data, deriving simple equations which predicted the results for the case studies.

6.1.1 Equations

The method estimates the evacuation time based on the effective width of the stairs and the total number of occupants which will be using the stairwell. The derived relationship is shown in Equation 4 and 5 below (Pauls, 1987) which are single line hand calculations to estimate total evacuation time (T) in minutes.

$$T = 0.68 + 0.081p^{0.73} \qquad \text{(Eq 4)}$$

p = occupants per metre (m_e) of effective stair width ($p \leq 800$)

$$T = 0.7 + 0.0133p \qquad \text{(Eq 5)}$$

p = occupants per metre of effective stair width ($p > 800$)

The buildings in the Pauls' data were indicated to be simultaneous uncontrolled evacuations. The study buildings were all 8-21 storeys high and Paul's indicates the error of predicted results from Equation 4 and 5 for 8-15 storey buildings was 0.2%. He notes the predictions are less accurate in taller buildings with lower populations per floor (Pauls, 1987).

The equation is indicated to predict the total time for an uncontrolled evacuation. The pre-evacuation time (referred to as start-up time) is given as 41 seconds (0.68 minutes) and is based on the time taken for the exit flow rate to reach half the mean flow (Pauls, 1987).

6.1.2 Modified Equation

Pauls' simplified hand calculation using Equation 4 and 5 from above includes an approximation for the pre-evacuation facet of the evacuation. Since this research focuses on the stair movement phase of the evacuation, the equation is modified to estimate only the time taken to descend the stairs.

To remove the pre-evacuation requires an approximation of Pauls' Equation 4 prediction. It is assumed that the empirical start-up time included in Equation 4 can be equated to the stair entry time of the case study data. Comparisons can then be made using the same stair entry time for the delay in the prediction line. Equation 4 is modified by removing the 0.68 to leave an empirical calculation of total egress time (Equation 6).

$$T = 0.081p^{0.73} \qquad \text{(Eq 6)}$$

p = occupants per metre of effective stair width ($p \leq 800$)

Using known case study stair entry times and calculating the stair movement time using Equation 6, a range for total egress time is estimated as a sum of the two values; the variability is equal to the stair entry distribution as the stair movement is a constant.

Individual descent rates can be estimated using the hand calculations, this requires the assumption that the estimated time is for the last occupant descending from the uppermost floor, as this appears to be typically where the occupant with the longest egress time is located. It is also assumed that the occupant will have a linear descent path.

This derived descent rate is plotted versus occupants from the case study data as well as agents from the model simulation. The stair entry times used for the derived descent rate lines are taken from the case study data;

- The minimum time is matched to the minimum stair entry time of the sampled case study occupant
- The maximum time is matched to the maximum stair entry time of the sampled case study occupant

The choice of stair entry time for the derived descent rate lines is to make comparisons of the performance alone, given little is known of what constituents the stair entry time in the case studies. This selection is maintained for the comparison with the model simulation data for consistency.

6.1.3 Comparisons

Two comparisons of Paul's hand calculation alongside model results and case study data are carried out;

1. The total egress time for all the occupants

This is the normal output format of the hand calculation. This result gives a coarse indication of the relative performance of the different results. However, the single number nature of the result can be misleading if the model results or case study data has outliers.

2. Individual descent plots

These plots show individual descent paths down the building. The plot shows descent speed and the floors where this may vary due to the situation within the stairwell. This is carried out using the modified Equation 6 as this is assumed to represent the stair movement.

6.2 Total Egress Time

6.2.1 Equation 4 Prediction

The results of the predicted total egress time using Equation 4 compared to the case study result is summarised in Figure 39. The general trend is Equation 4 predicts total egress times from 6% to 38% shorter than the case study data. Manchester Clean Stair and Christchurch Stair A had the smallest difference of 9.4% and 6.0% respectively.

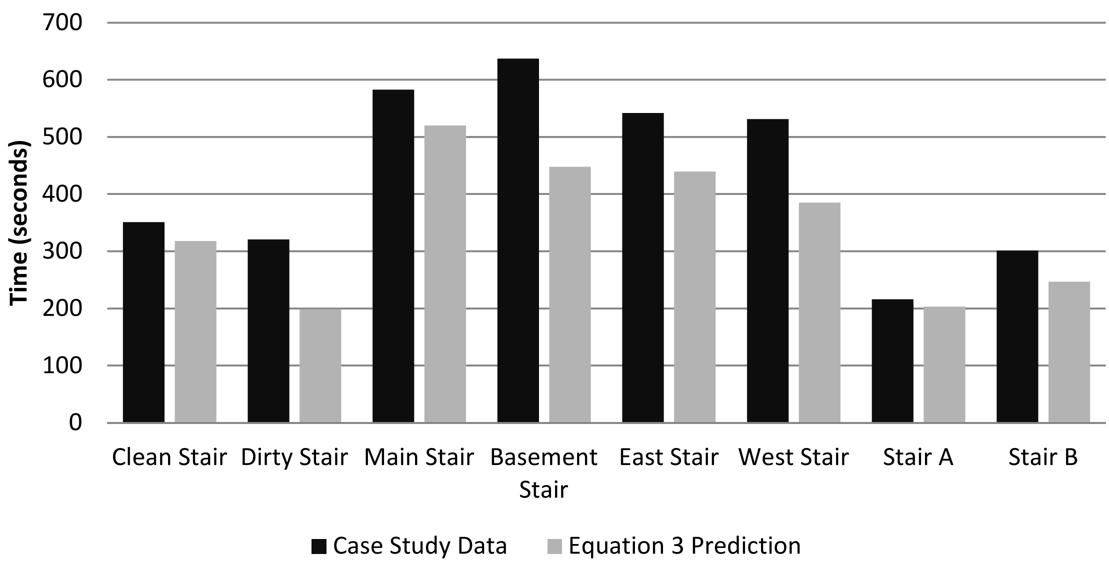

Figure 39: Total Egress Time Bar Plot for Pauls' Hand Calculation Prediction (Eq 4) Compared to Case Study Results

Table 18 summarises the total egress time calculation for the case study stairs using Equation 4 from above; as every case study stair population is less than 800, Equation 5 is not used. The total evacuation time is converted from minutes to seconds. The effective width is calculated as the width dimension given in Chapter 2 and subtracting 0.30 m for two boundary layers (0.15 m for each boundary).

Table 18: Predicted Total Egress Times for Case Study Stairs using Equation 4

Building	Stair	Estimated Total Egress Time (seconds)	Population	Effective Stair Width (m)
Manchester	Clean	318	168	0.65
	Dirty	199	79	0.67
Majestic	Main	520	377	0.70
	Basement	448	302	0.70
Unisys	East	440	312	0.75
	West	385	255	0.75
Christchurch	A	204	88	0.72
	B	247	122	0.72

The total egress time predicted by Equation 4 is proportional to the population for stairs with similar effective widths. The Majestic Main stair has a stair width of 1.0 m and has the largest population per metre of effective stair width (m_e) with 538.5 people/m_e. The Manchester Dirty stair has a stair width of 0.98 m and has the smallest population per metre of effective stair width (m_e) with 117.9 people/m_e.

6.2.2 Modified Equation 6 Prediction

The results of the predicted total egress time using the modified Equation 6 compared to the case study result is summarised in Figure 40. Overall, Equation 6 predicts total egress times with a difference of 0.9% to 31% to the case study results. The Eq. 6 total egress times were generally shorter than the case study, with Manchester Clean stair and Christchurch stair A being slightly longer. The Majestic Main stair and Christchurch stair B were close (less than 10%) to the case study results.

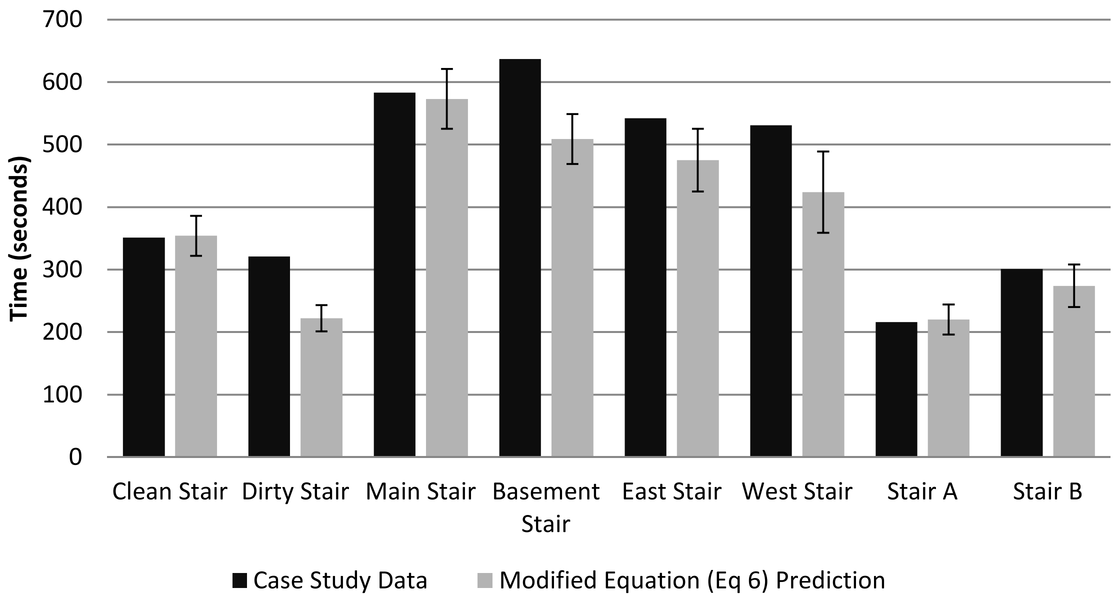

Figure 40: Total Egress Time Bar Plot for the Modified Pauls' Equation (Eq 6) Compared to Case Study Results

Table 19 summarises the total egress time calculation for the case study stairs using the modified Equation 6. The total evacuation time is calculated as described for Table 18 above. The case study stair entry distributions from Chapter 2 are added to Equation 6 value, this give an estimated total egress time average with a standard deviation equal to that from the stair entry distribution.

Table 19: Modified Pauls' Equation (Eq 6) with Case Study Stair Entry Distribution Total Egress Time

Building	Stair	Modified Pauls' Equation (Eq 6) (seconds)	Case Study Stair Entry Averages (seconds)	Estimated Total Egress (seconds)
Manchester	Clean	277	77 ± 32	354 ± 32
	Dirty	158	64 ± 21	222 ± 21
Majestic	Main	479	94 ± 48	573 ± 48
	Basement	408	101 ± 40	509 ± 40
Unisys	East	399	76 ± 50	475 ± 50
	West	344	90 ± 65	424 ± 65
Christchurch	A	162	58 ± 24	220 ± 24
	B	206	68 ± 34	274 ± 34

6.3 Individual Descent Charts

The results for average descent speed for sampled individuals from the individual descent charts is summarised in Table 20. Overall, five out of the eight stairs have a modified Equation 6 descent speed slower than the sampled case study occupants. The Majestic Main stair is similar and two stairs; Manchester Dirty and Majestic Basement are faster, by 0.21 m/s and 0.07 m/s respectively.

The estimated descent speeds for the case study occupants is taken from the descent comparison in Chapter 5. The modified Equation 6 descent speed is calculated in Table 21.

Table 20: Summary Table of Modified Equation 6 Prediction Individual Descent Speed Results Compared to Case Study Results

Building	Stair	Average Case Study Descent Speed (m/s)	Modified Equation 6 Descent Speed (m/s)
Manchester	Clean	0.64 – 0.68	0.51
	Dirty	0.39 – 0.71	0.92
Majestic	Main	0.41 – 0.63	0.50
	Basement	0.63	0.70
Unisys	East	0.38 – 0.42	0.31
	West	0.45 -0.47	0.33
Christchurch	A	0.49 – 1.27	0.45
	B	0.22 – 0.90	0.35

6.3.1 Typical Descent Chart

An example of a typical individual descent chart is shown for Manchester Dirty stair (Figure 41), with the floor number on the y-axis and the time in seconds is along the x-axis. The case study occupants are represented by a solid black line, the modified Equation 6 descent rate is shown with a dashed red line. Individual descent charts for other stairs can be found in Appendix III, as well as comparison charts with model agent's descent.

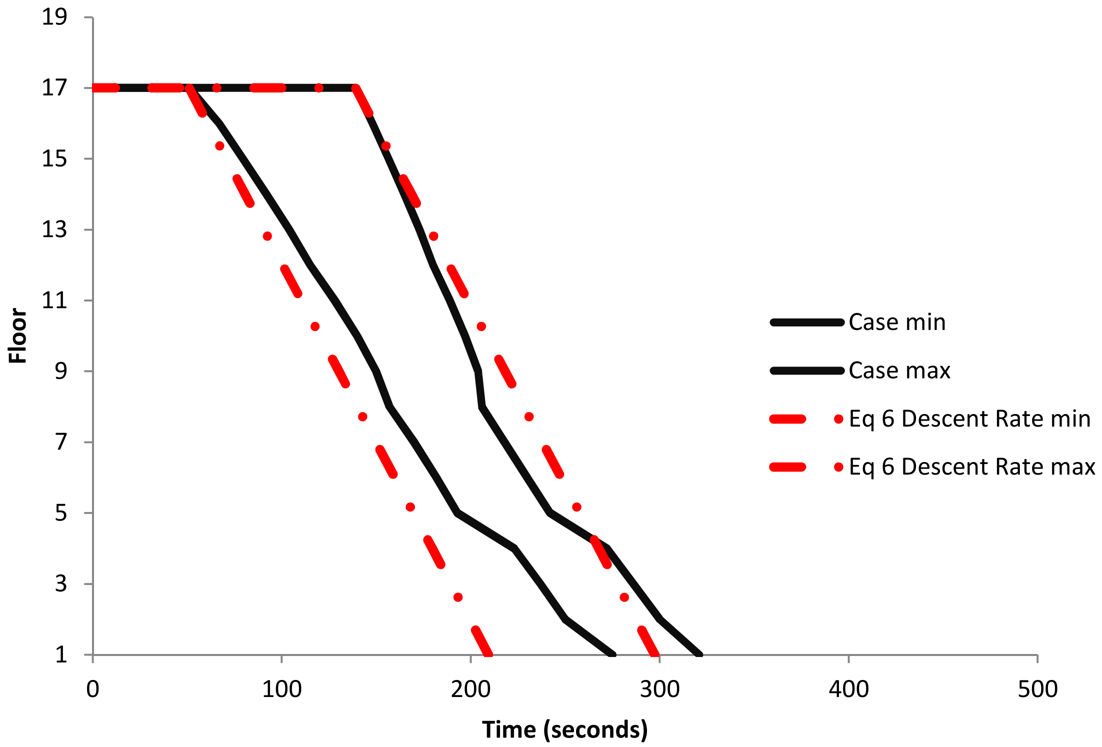

Figure 41: Manchester Dirty Stair Case Study Occupants Compared with the Derived Descent Rate

The total egress time prediction of equation 6 using the Manchester Dirty stair entry times are similar to the case study for both sampled occupants (Figure 41), except for the case study slowing near the end. The prediction line's speed of 0.92 m/s is close to the case study occupant of 0.93 m/s. The other case study occupant speed is 0.71 m/s; both occupants then slow to approximately 0.39 m/s.

6.3.2 Descent Rate Calculation

The descent rate (Table 21) is calculated from the total time calculated from Equation 6, divided by the number of floors from the top floor to the exit floor. The number of floors to descend is taken from the case study data described in Chapter 2.

Table 21: Descent Rate Approximation from Equation 6

Building	Stair	N# of Floors to Descend	Descent Rate (seconds/floor)	Descent Speed (m/s)
Manchester	Clean	16	17.3	0.51
	Dirty	16	9.9	0.92
Majestic	Main	20	24.0	0.50
	Basement	24	17.0	0.70
Unisys	East	14	28.5	0.31
	West	13	26.5	0.33
Christchurch	A	10	16.2	0.45
	B	10	20.6	0.35

Decent rates for the case study stairs ranged from 9.9 s to 28.5 s per floor. The corresponding descent speed is calculated as the total travel distance per floor in the line of travel divided by the descent rate. Speeds ranged from 0.31 m/s – 0.92 m/s.

7 Discussion

7.1 Comparisons to Case Study Data

7.1.1 EvacuatioNZ Computer Model

Overall, five out of eight of the ENZ computer model stair's results are close (within 10%) to the case study data. In the stairs where the computer model results were different by more than 10%, they were conservative. Model results had single standard deviations between 5-20 seconds, which is a smaller variation compared to the distribution on the stair entry inputs.

The Manchester building ENZ predicted total egress times that were significantly longer than the case study result. due to the rate of descent of the case study occupants being faster than the model prediction, demonstrated by the cumulative evacuation and individual descent charts. It is not certain why the model prediction is slower than the case study in this particular case but not to the same extent in the other case study buildings. The distribution of stair entry delays may have created more optimum stair conditions or the specific characteristics of the building occupants influence the performance. The difference is more pronounced in the Dirty stair, which has a very low population.

Min-max cumulative charts demonstrated that the model and case study performance in terms of final egress flow rates are not significantly different. Gradients (flow rates) are similar in five out of the eight stairs. Another two stairs have similar flow rates but the model results do not encompass the case study results.

The sampled individuals from the model and case study for descent charts have similar comparisons as previous outputs. Overall, descent performance (using average descent speed) was not significantly different, in some stairs the model result is not as close to the case study result; particularly the Manchester building. Both Manchester ENZ stair models are slower than the case study occupants.

The ENZ model results were generally close in terms of total egress time, egress flow rate and have a slower descent speed in six out of the eight stairs. Although ENZ did not match the exact behaviour exhibited in some of the case study data, particularly Unisys West stair, ENZ did display very similar trends in most stairs.

7.1.2 Convergence

There is not a clear link between number of simulations for convergence and the end result for a given stair model. The stair models had a range for the number of simulations before convergence was achieved, from 21 up to 177 simulation runs. The sample pool is not large enough to determine statistical trends. It is also to be expected that due to the pseudo-random nature of some of the model algorithms, the number of simulations required to reach convergence varies each time the batch is run.

7.1.3 Pauls' Simplified Equation

The first comparison is of the unmodified hand calculation using Equation 4 is shorter than the case study results by 6% to 38%. Two stairs, Manchester Clean and Christchurch A were closest with a 9% and 6% shorter time respectively.

The modified Equation 6 total egress times had total egress times closer to the case study than Eq. 4. Overall, the difference to the case study results was 0.9% to 31%. Only two stairs were longer than the case study; Manchester Clean and Christchurch Stair A, with 0.9% and 1.9% respectively. Majestic Main was also close with a shorter time by 1.7%.

The modified Equation 6 achieved results which were closer to the case study results, but in general were still shorter. Five out of the eight stairs were shorter by a margin greater than 10%. The stair entry distribution brought the totals closer but does not change the above observations.

The results rely on the interpretation of Pauls' equation in terms of equating the pre-movement value in Pauls' equation to the stair entry time from the case study data. The source paper (Pauls, 1987) for the hand calculation relates the first 0.68 value in the equation as an abstraction of the start-up time. This is interpreted as an averaged value for the pre-evacuation distributions present in the multi-storey buildings, quoted as 0.68min (approximately 41 seconds) in the source paper. Equation 6 removes this value, which may not be accurate with the intention of the equation.

7.1.4 Descent Speed

Case study occupants had average speeds ranging from 0.3 m/s to 1.27 m/s, most averaged speeds in the range of 0.4 m/s to 0.6 m/s. Model agents have speeds ranging from 0.2 m/s to 0.9 m/s, most averaged speeds in the range of 0.3 m/s to 0.7 m/s. The modified Equation 6 has speeds which range from 0.31 m/s to 0.92 m/s and the prediction curve for each stair is a constant descent speed.

Referring to Table 1 in Chapter 1, the average speeds of both the case study occupants and model agents fall within the 0.2 m/s to 0.76 m/s for a range of densities quoted for Fruin (1987). The Eq. 6 curves are, on average faster. The averages of Lord et al. of 0.52 m/s ± 0.23 m/s and 0.52 m/s ± 0.24 m/s for young and old males respectively are also close to case study, model speeds and the Eq. 6 curves, particularly the general averages.

7.1.5 Stair Entry

Stair entry times were a difficult variable to control, this was substituted for pre-evacuation time input in the model setups. Larger variations in stair entries or for buildings with lower populations increased the range of egress times for the model. The model did not achieve results as close to the case study data in these scenarios. It is also suspected that the distribution of delays to occupants can have an impact on the total evacuation performance of the stairs; for example causing large numbers of occupants from different floors to encounter each other in the stairs or not.

The impact of stair entry distributions is likely demonstrated in the Unisys West stair. In this stair, case study occupants consistently experienced long delays while descending the stairs. This appears to be at least partially due to when groups entered the stairs. The ENZ model results reproduced similar delays. However, sometimes the agents did not experience any delays while descending the stairs and with the only variable between simulations within a batch being the stair entry, reinforcing this as a likely cause.

Stair entry distributions were not significantly investigated however, as it is not possible to estimate the portion of the time which was used for pre-evacuation activities and how long occupants spent travelling to the stair and possibly queuing before entering the stair. The impact of worst case stair entry or pre-evacuation times, based on interactions between floors should be investigated further.

7.2 The EvacuatioNZ Model

7.2.1 Stair Layout Input

In previous research for stairs in ENZ the representation was of the landing as a node and the stairs as a connection (arc). However, it was pointed out by Tsai (2007) that this misrepresented the standing space that might be available in a stair flight itself. Tsai suggested that the stairs and landing be represented either in a single node of appropriate dimensions or separate nodes for each element.

The sensitivity analysis investigated both of Tsai's suggested layouts as well as an additional layout representing any mid-flight landings with another node. The last layout, referred to as a complex B layout in this research, is demonstrated to provide the closest results to the case study buildings in sensitivity analysis. Further analysis representing the rest of the stairs predicted results similar to the case study results, despite the type of stairs being different in all three of the buildings which were approximated with the complex B layout.

No direct correlation can be made about the relative accuracy of the layout based on stair type, such as half-turn or scissor as other factors varied between the buildings; such as stair width, tread and riser dimensions, the building height and number of occupants. Additional data points for each stair type is necessary and recommended as further work for representing stairs in a node network model.

7.2.2 Agent Input

Input parameters for the computer model agents can vary from very detailed (case study research comparisons) to more general (design scenarios). Clearly, the more complex algorithms the model uses, the more detailed the inputs need to be. However, in many cases there is not enough case study data for detailed inputs. Designers will often have a unique scenario the case study research has not covered, and as a result inputs are more general with the associated assumptions and required safety factors.

This research investigated varying the detail of inputs from the case study data. The results indicated that using a range of values or distribution for the input combined with running large numbers of simulations produced similar trends to more specified inputs, in relation to the case study results.

The trend is expected given the distributions are based off the range of specific data available from the case study. Running large numbers of simulations would reproduce a range of results with some variation to what might be expected for specific inputs. The primary variation is between allocating the stair entry time to an occupant that started on a given floor, as opposed to the agent being randomly assigned a stair entry based on a distribution of all the stair entry times from the case study data.

This result of the model is useful for future case study research as reasonable comparisons might be made without the need for very specific information of the occupants, which can be difficult and expensive to obtain. It is recommended that further work should be carried out using building wide distributions as an input, simulated a large number of times. The work may reveal if there is a similar trend in the same buildings with different evacuation conditions as well as other buildings.

7.2.3 Sensitivity Observations

An observation from the agent variation type 3 simulations is the minor variation in results between simulations. The agent inputs were specified and therefore did not change between simulations; hence the variation in results must be due to how the model moves agents down the stairs. In buildings with lower populations there was little to no variation.

This demonstrates the pseudo-random algorithm used for selecting agents to move into open nodes is working. How well this represents actual building population behaviour would need to be investigated further and require multiple sets of case study data from a single building.

7.2.4 Advantages and Disadvantages

There were advantages in using ENZ due to the type of model it is and the nature in which the program processes input and outputs. However, there were also limitations of the model. Some of the relevant factors are;

1. Ease of use: ENZ is an easy model to set up, with the use of the graphml interface. The modelling space is represented by nodes which are abstracted and do not rely on uploading or drawing the building plan

   The inputs for the model can also range from simple to more complex depending on the users requirements or available data. These can be changed relatively quickly, allowing flexibility in carrying out sensitivity before applying more complex parameters. However, the level of complexity for occupant decision making is currently limited to exit choice decision making and pseudo-random algorithms for merging.

   The style of input using xml code can take some learning for some users. Once set up, the layout can be copied and modified for different purposes. The user must be familiar with the abstractions made by the model as this can be less intuitive than more complicated models.

2. Fast simulation time: The abstraction of the layout allows the ENZ model to run simulations quickly, in less than 15 seconds on default settings.

Introducing more complexity to the layout, or frequency of the calculations (by reducing time steps) increases the simulation time.

The short simulations allow for large numbers of simulations to be run for a set of parameters. This can allow distributions to average out or demonstrate the variability of single inputs.

The model uses simpler algorithms to achieve the short simulation times and does not include complicated people, group or room geometry interactions which are prevalent in recent egress models.

3. Distributions for inputs and outputs: This functionality works well with the model's ability to quickly run a large number of simulations. Risk based assessment often requires a range of scenarios or inputs. This model can produce outputs which are a distribution or range.

Outputs require processing by the user post simulation to produce graphical results as ENZ currently does not have a graphical output capability.

7.3 Research Limitations

The research is conducted on a relatively small number of building stairs, as well as only having a single data point for each stair evacuation. Case study research needs to continue to strive for consistency, quality and quantity of data for multi-storey building evacuations. Ideally, future research will involve multiple data points from each building recorded in a similar format to allow deeper comparisons into the relationship of height and stair configuration.

In addition, the trial evacuation data was only carried on a relatively small range of building heights. Current high rise buildings are reaching up to 100 stories high and more, while this research looks at buildings of 10 to 27 stories high. The results of an evacuation from a taller building are likely to involve other factors, or exacerbate factors which may not have been noticeable in the trial evacuations this research analyses.

The research considered the performance of occupants descending the stairs as no data was available on the pre-evacuation phases. As Kuligowski (2008) has stated and some data in this work further supports, pre-evacuation can have a significant impact on the performance of an evacuation. Not only in terms of delay before moving down stairs begins, but also in the formation of groups and the interactions with other groups within the stair.

Finally, this research primarily considers the overall performance of evacuation – individual performance was not extensively investigated. Unusual behaviour did occur, particularly in the Unisys West stair where the interaction between large numbers of each floor's population due to stair delay times resulted in very slow descent times. This is primarily due to crowding in the stairs and increased amounts of stair merging.

8 Conclusion

EvacuatioNZ could be used as a tool for predicting evacuations from multi-storey building given the recommendations from this research and further work on the range of buildings, population and pre-evacuation behaviour is carried out.

Based on this research, Pauls' hand calculation method is not recommended for predicting total evacuation times in contemporary multi-storey buildings, predicting significantly shorter evacuation times. Modifying the equation improved the result, but 6 out of the 8 stairs predicted total evacuation times were still shorter than the case study data.

8.1 Recommendations for EvacuatioNZ Modelling of Multi-Storey Building Stairs

- Time step should be set to 0.5 seconds; or even 0.1 seconds if the modelling time and effort is available to reduce rounding artefacts. 0.5 second time steps have been shown to be a good compromise between simulation time and fidelity.
- Stairs should be represented as closely as possible; Floor and mid-floor landings (where present) should have a node and connector each. As well as each stair flight between should have a node and connector. Presets could be adopted for the interface to reduce on nodes required to build a multi-storey stairwell
- A large number of runs should be carried out for each scenarion, even with many of the inputs defined, the pseudo-random performance / decision making of occupants will result in a variance in the final performance. Hence, single simulations run a risk of outputting a result which may come from an extreme end of the possible results

8.2 Contemporary Stair Evacuation Performance and Predictions

The case study occupant's performance was compared to the EvacuatioNZ computer model and Pauls' simplified hand calculations for multi-storey evacuation.

- In three of the four buildings EvacautioNZ predicts a total egress time within 15% of the case study results. In the fourth, EvacuatioNZ predicts a total egress time from 30% to 59% longer. On average, EvacuatioNZ predicted times have a difference of 8.6% with case study results

- EvacuatioNZ cumulative egress (exit flow rate) and individual descent (descent speed) comparisons have similar curves to the case study results. In terms of exit flow rate and descent speed the EvacuatioNZ results are on average, within 10% of the case study in five out of the eight stairs

- Pauls' simplified hand calculation (Eq. 3) predicts total egress times 6 to 38% shorter than the case study results. This prediction improves to a difference of 0.9 to 31% when using a modified version of the hand calculation (Eq. 6). In the latter case, five out of the eight stairs are within 10% of the case study

- Using the modified Eq. 6, the approximated individual descent curves are similar to case study occupants when stair entry times are matched. On average, Eq. 6 curve descent speeds are slower than the case study occupants

8.3 Further Work

- The EvacuatioNZ model could develop to include further detail in stairs, particularly with regards to handrails and boundary layers. Currently, the boundary layer is automatically calculated and it is recommended to have this as a selectable option with choices for a wall boundary, handrail boundary or custom user specified

- Further research is needed on the performance of ENZ when modelling buildings with lower population density evacuations, as there is a consistently different result for the two stairs with much lower populations

- More data is needed from case studies, ideally multiple sets of data from a single building at different times as Gwynne et al describes. The new case study data should strive to include detail on the occupants prior to entering the stairs

- Similar further comparisons should be made with a larger set of case study buildings in which to verify the conclusions of this work. Buildings with larger populations per floor would complement the case study buildings of this research

- Pending case study data for taller buildings, comparisons should be made to occupants descending larger numbers of floors during an evacuation. As the prediction methods in this research assume constant performance throughout an evacuation, the methods may be less accurate for occupants who tire from descending large numbers of stairs

- Study on the relationship between occupant characteristics and the variation in results could be carried out with this case study data with the addition of more data buildings or points. Reasonable observations should be able to be made, particularly about obesity and age in relation to speed

- Trial evacuation data should include more details about occupants – start floor, BMI, age, disabilities (if any), gender and somehow associate this with video footage data. This would allow researchers to quantify typical building population distributions and relate this to the performance of the building

- Using the different layout suggested in this research, further comparisons should be done with other computer models

- Further investigation into the impact of group interactions in the stairs due to entry time delay, for example when large groups of people enter the stairs and encounter other large groups due to the alignment of their respective stair entry delay

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Appendix I – Case Study

Floor by floor																	
		Level 9															
		46	47	50	53	54	55	56	57	59	64	65	80	88	58	78	84
		M	M	M	M	M	M	M	M	M	M	M	M	F			
Ground (L1)		6:29	6:32	6:36	6:37	6:38	6:40	6:42	6:44	6:47	6:53	6:54			6:46		
	3:48	2:41	2:44	2:48	2:49	2:50	2:52	2:54	2:56	2:59	3:05	3:06	3:26	3:37	2:58	3:23	3:34
		0:20	0:21	0:21	0:20	0:20	0:21	0:21	0:21	0:21	0:21	0:21	0:19	0:19	0:22	0:19	0:19
L2		6:57	6:59	7:03	7:05	7:06	7:07	7:09	7:11	7:14	7:20	7:21	7:43	7:54	7:12	7:40	7:51
	4:36	2:21	2:23	2:27	2:29	2:30	2:31	2:33	2:35	2:38	2:44	2:45	3:07	3:18	2:36	3:04	3:15
		0:36	0:36	0:35	0:35	0:35	0:34	0:35	0:34	0:34	0:35	0:35	0:33	0:34	0:34	0:34	0:34
L4		7:24	7:26	7:31	7:33	7:34	7:36	7:37	7:40	7:43	7:48	7:49	8:13	8:23	7:41	8:09	8:20
	5:39	1:45	1:47	1:52	1:54	1:55	1:57	1:58	2:01	2:04	2:09	2:10	2:34	2:44	2:02	2:30	2:41
		0:19	0:19	0:20	0:20	0:21	0:21	0:21	0:18	0:18	0:18	0:17	0:17	0:17	0:18	0:18	0:17
L5		7:36	7:38	7:42	7:44	7:44	7:46	7:47	7:53	7:56	8:01	8:03	8:27	8:37	7:54	8:22	8:34
	6:10	1:26	1:28	1:32	1:34	1:34	1:36	1:37	1:43	1:46	1:51	1:53	2:17	2:27	1:44	2:12	2:24
		0:16	0:16	0:17	0:17	0:15	0:14	0:13	0:15	0:14	0:14	0:14	0:16	0:16	0:14	0:15	0:16
L6		7:52	7:54	7:57	7:59	8:01	8:04	8:06	8:10	8:14	8:19	8:21	8:43	8:53	8:12	8:39	8:50
	6:42	1:10	1:12	1:15	1:17	1:19	1:22	1:24	1:28	1:32	1:37	1:39	2:01	2:11	1:30	1:57	2:08
		0:17	0:17	0:17	0:17	0:17	0:14	0:14	0:14	0:13	0:13	0:13	0:15	0:13	0:14	0:14	0:14
L7		8:02	8:04	8:07	8:09	8:11	8:17	8:19	8:23	8:28	8:33	8:35	8:55	9:07	8:25	8:52	9:03
	7:09	0:53	0:55	0:58	1:00	1:02	1:08	1:10	1:14	1:19	1:24	1:26	1:46	1:58	1:16	1:43	1:54

Figure I - 1: Example of Raw Case Study Data With Camera Recoded Times (minutes), Normalised Times (minutes) and Time between Floors (seconds)

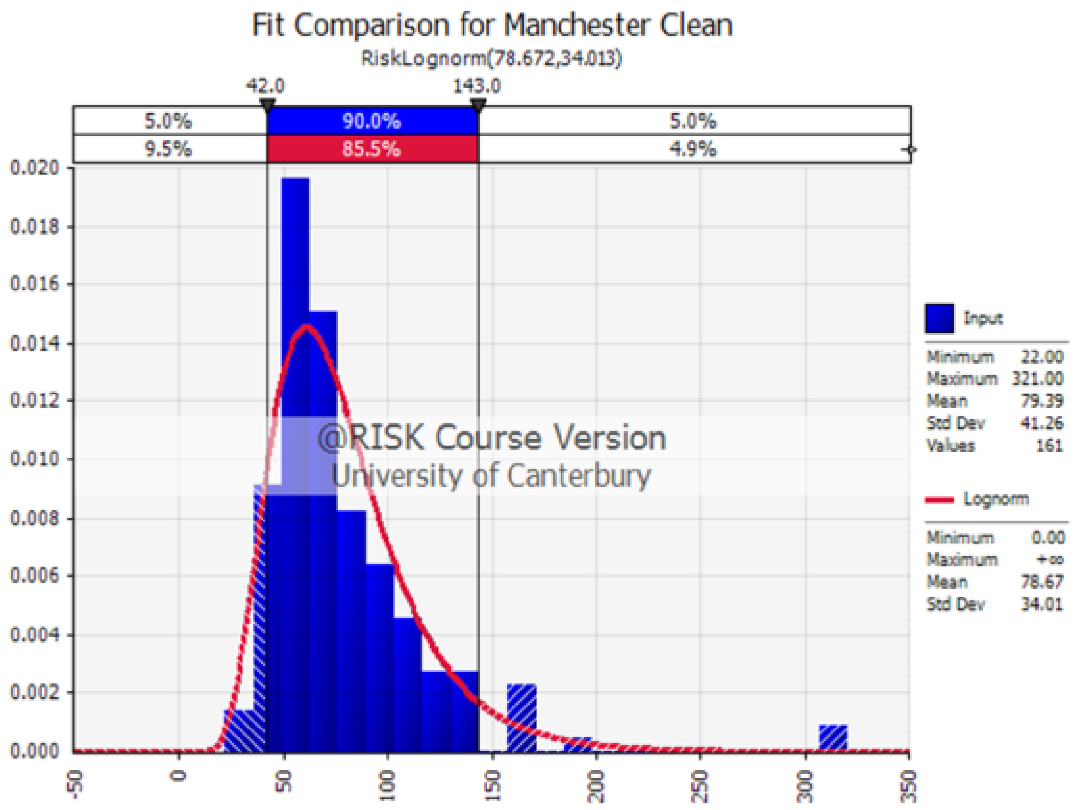
East Stair				Level 8											Level 9
0:00 = 9:30:00		73	86	103	5	77	117	118	53	54	55	66	67	68	76	116	46
	M/F	F	F	F	M	M	M	M	F	F	F	F	F	F	F	F	M
FE		17:47	18:11	18:44	15:45	17:54	19:12	19:12	17:19	17:20	17:20	17:38	17:39	17:40	17:53	19:10	17:02
	14:05	3:42	4:06	4:39	1:40	3:49	5:07	5:07	3:14	3:15	3:15	3:33	3:34	3:35	3:48	5:05	2:57
4 to 3		13:59	14:19	14:50	12:03	14:05	15:17	15:17	13:28	13:29	13:31	13:49	13:50	13:52	14:03	15:15	13:15
	11:06	2:53	3:13	3:44	0:57	2:59	4:11	4:11	2:22	2:23	2:25	2:43	2:44	2:46	2:57	4:09	2:09
5 to 4		13:21	13:43	14:14	11:36	13:28	14:39	14:41	12:49	12:51	12:52	13:11	13:13	13:14	13:26	14:39	12:36
	10:47	2:34	2:56	3:27	0:49	2:41	3:52	3:54	2:02	2:04	2:05	2:24	2:26	2:27	2:39	3:52	1:49
6 to 5		14:58	15:18	15:52	13:24	15:04	16:17	16:18	14:20	14:25	14:28	14:47	14:48	14:50	15:02	16:15	14:13
	12:43	2:15	2:35	3:09	0:41	2:21	3:34	3:35	1:37	1:42	1:45	2:04	2:05	2:07	2:19	3:32	1:30
7 to 6		14:07	14:30	15:00	12:52	14:15	15:38	15:39	13:23	13:24	13:28	13:45	13:47	13:48	14:13	15:35	13:17
	12:18	1:49	2:12	2:42	0:34	1:57	3:20	3:21	1:05	1:06	1:10	1:27	1:29	1:30	1:55	3:17	0:59
		x	x	x													
8 to 7					12:15	12:55	14:31	14:34	12:38	12:39	12:41	12:44	12:46	12:45	12:51	14:28	12:34
	11:48				0:27	1:07	2:43	2:46	0:50	0:51	0:53	0:56	0:58	0:57	1:03	2:40	0:46
					x	x	x	x	x	x	x	x	x		x	x	
9 to 8																	11:47
	11:13																0:34

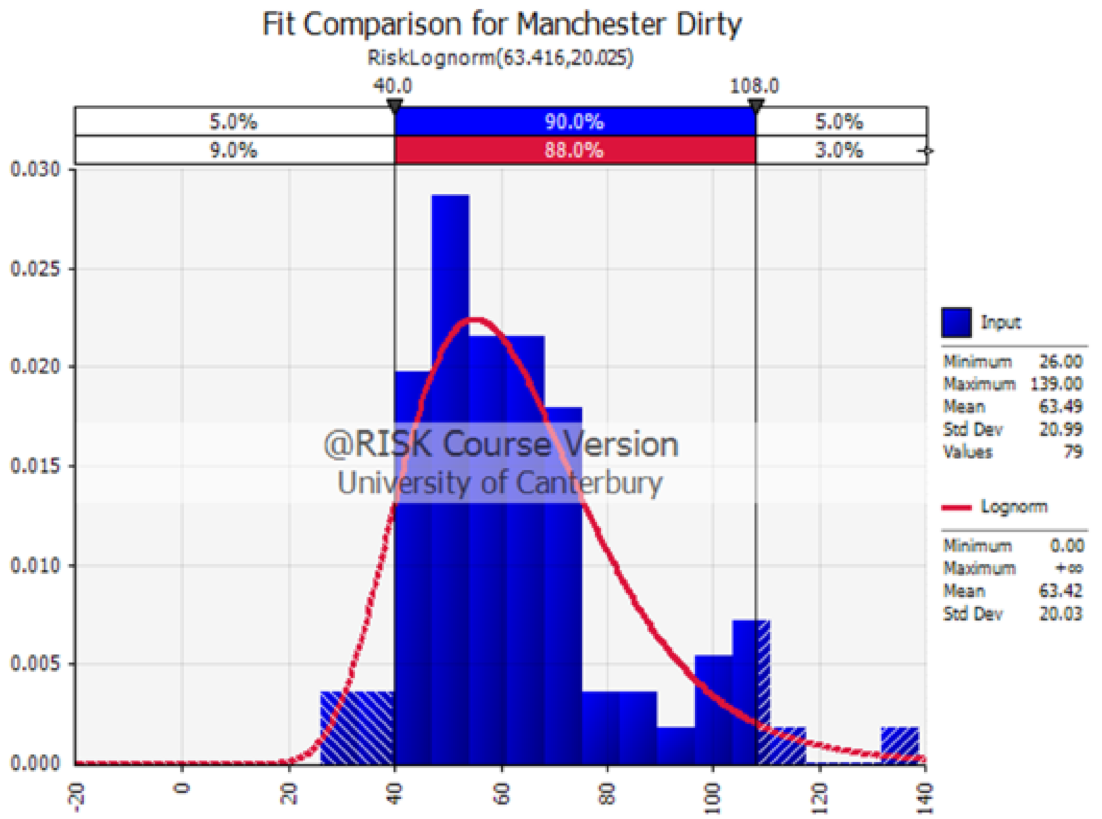
Figure I - 2: Second Example of Raw Case Study Data with Camera Recoded Times (minutes), Normalised Times (minutes) and Time between Floors (seconds)

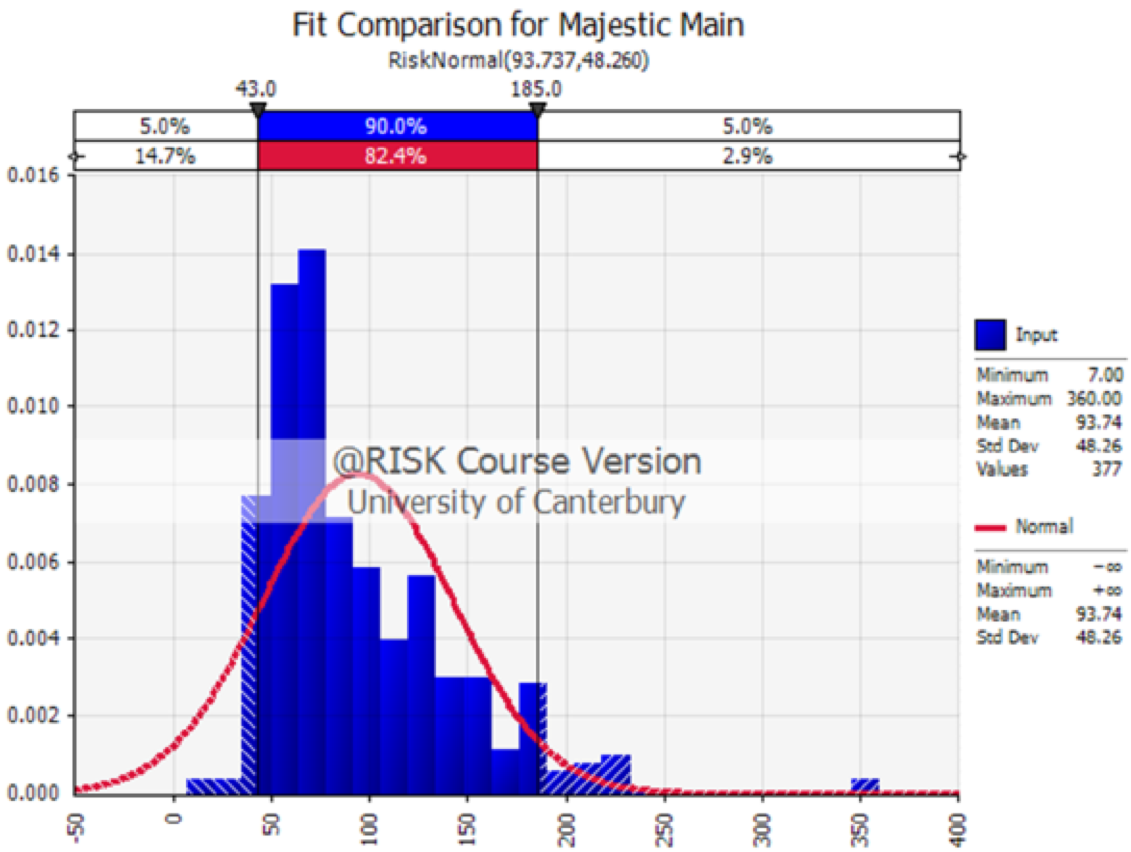
		Level 13											Level 14				
M/F	F	M	M	M	M	F	F	F	F	F	F	F	M	M	M	M	
Occupant	180 (181)	132 (38)	171 (94)	181 (113)	183 (114)	145 (45)	162 (60)	163 (61)	170 (94)	182 (111)	203 (202)	211 (219)	136 (35)	146 (39)	164 (48)	169 (53)	176
Evac time (est)	401.0	326.0	390.0	410.0	413.0	349.0	376.0	378.0	389.0	412.0	442.0	456.0	337.0	350.0	379.0	388.0	
4.0	350.0	271.0	338.0	354.0	356.0	294.0	325.0	327.0	337.0	355.0	389.0	402.0	280.0	297.0	328.0	335.0	
5.0	334.0	256.0	320.0	337.0	339.0	279.0	307.0	309.0	319.0	337.0	372.0	388.0	264.0	280.0	309.0	316.0	
6.0	314.0	237.0	303.0	315.0	318.0	258.0	291.0	292.0	302.0	316.0	354.0	369.0	245.0	261.0	293.0	299.0	
7.0	297.0	220.0	283.0	299.0	302.0	241.0	272.0	273.0	282.0	300.0	335.0	349.0	228.0	243.0	274.0	281.0	
8.0	280.0	202.0	268.0	282.0	286.0	224.0	255.0	256.0	267.0	283.0	318.0	334.0	209.0	227.0	257.0	265.0	
9.0	261.0	162.0	246.0	263.0	266.0	203.0	234.0	234.0	246.0	264.0	300.0	315.0	170.0	207.0	235.0	242.0	
10.0	239.0	97.0	225.0	242.0	244.0	168.0	212.0	214.0	224.0	243.0	280.0	296.0	111.0	169.0	215.0	222.0	
11.0	220.0	78.0	190.0	222.0	225.0	96.0	174.0	175.0	189.0	224.0	259.0	274.0	85.0	98.0	176.0	187.0	
12.0	181.0	50.0	117.0	183.0	186.0	73.0	104.0	101.0	116.0	184.0	239.0	254.0	56.0	78.0	103.0	114.0	
13.0		38.0	94.0	113.0	114.0	45.0	60.0	61.0	94.0	111.0	202.0	219.0	42.0	48.0	63.0	92.0	
14.0													35.0	39.0	48.0	53.0	
15.0																	
16.0																	
17.0																	

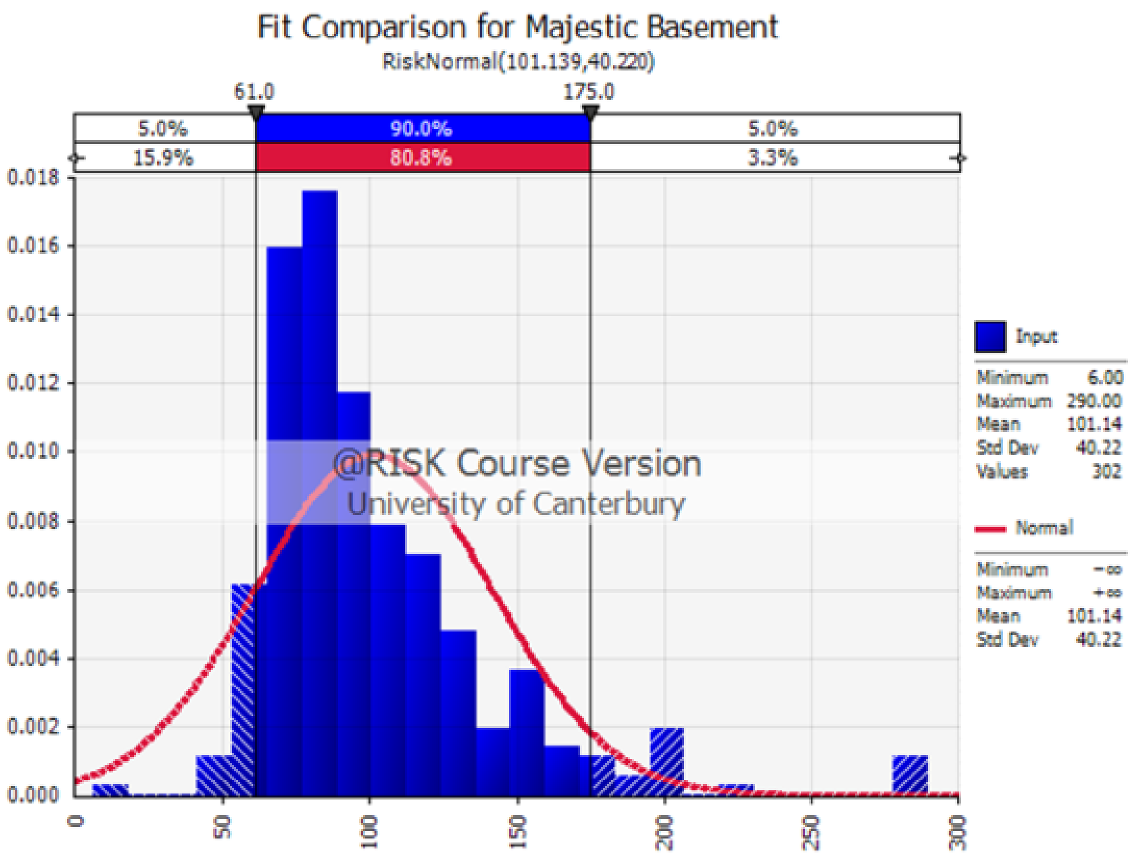
Figure I - 3: Processed Case Study Data Showing Time After Evacuation Start (Seconds) when Sighted on Each Floor

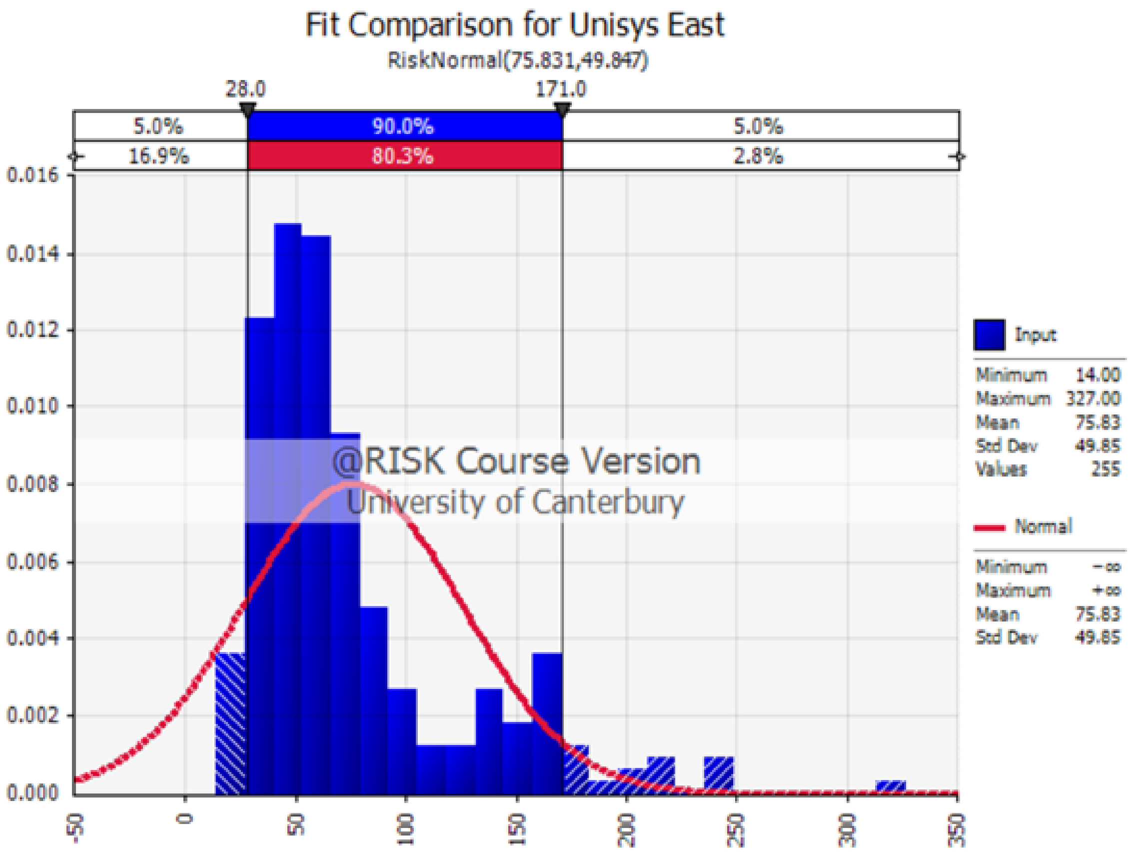
Figure II - 1: Normal and Log-Normal @Risk Best Fit Curves for Case Study Stair Entry Time Data

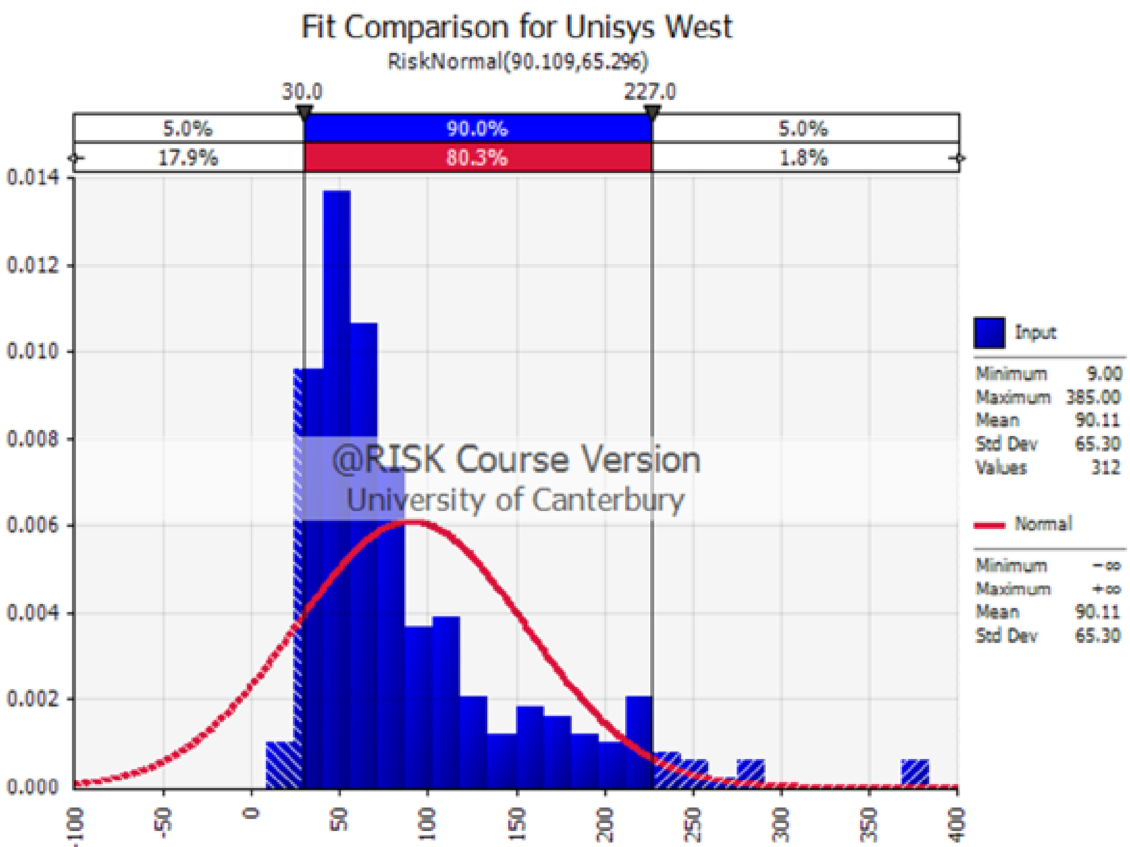


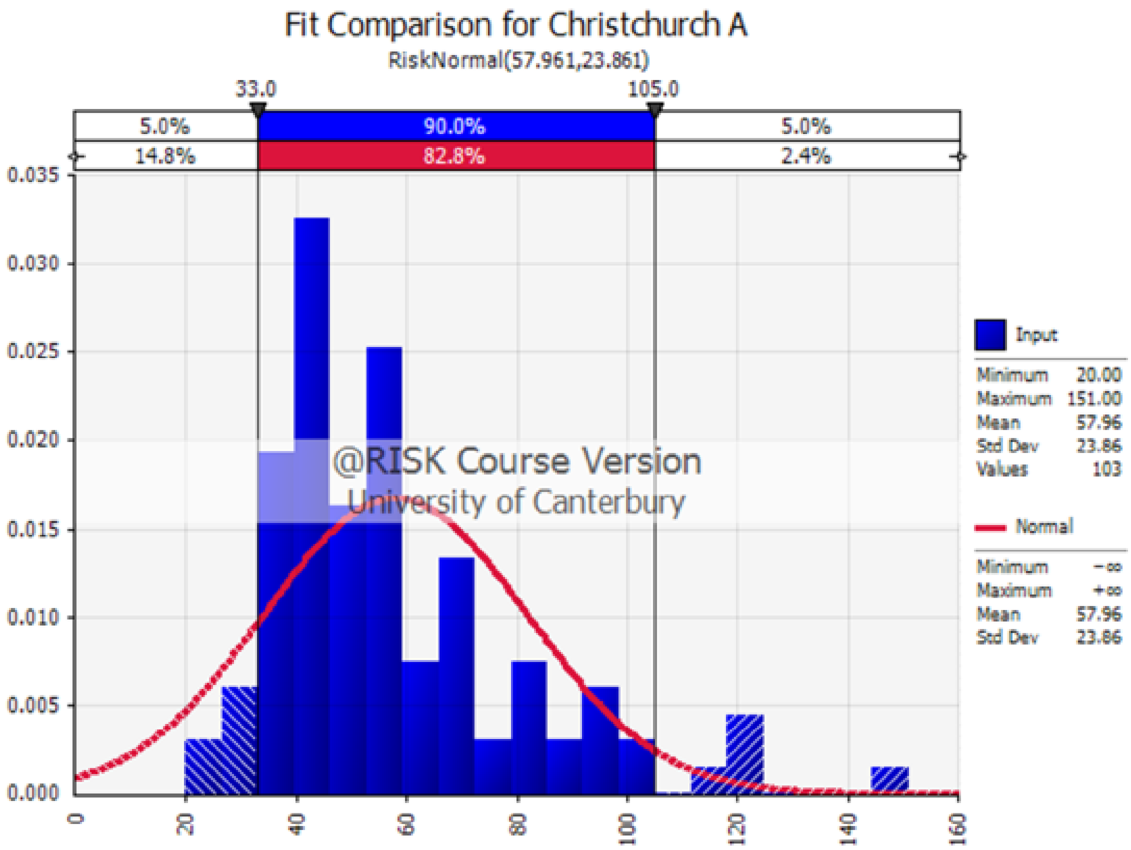



Fit Comparison for Majestic Main
RiskNormal(93.737,48.260)
43.0
185.0
5.0%
90.0%
5.0%
14.7%
82.4%
2.9%
@RISK Course Version
University of Canterbury
Input
Minimum 7.00
Maximum 360.00
Mean 93.74
Std Dev 48.26
Values 377
Normal
Minimum −∞
Maximum +∞
Mean 93.74
Std Dev 48.26

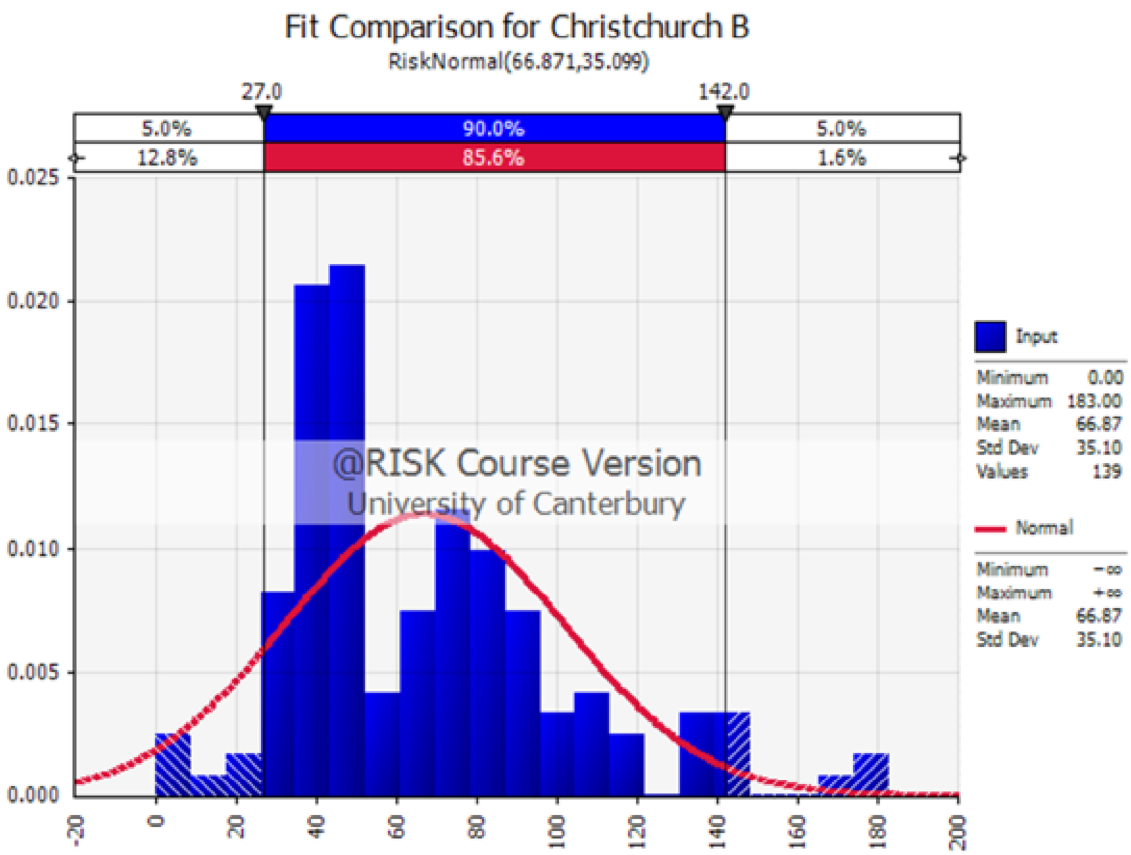

Fit Comparison for Majestic Basement
RiskNormal(101.139,40.220)
61.0
175.0
5.0%
90.0%
5.0%
15.9%
80.8%
3.3%
@RISK Course Version
University of Canterbury
Input
Minimum 6.00
Maximum 290.00
Mean 101.14
Std Dev 40.22
Values 302
Normal
Minimum −∞
Maximum +∞
Mean 101.14
Std Dev 40.22


Fit Comparison for Unisys East
RiskNormal(75.831,49.847)
28.0
171.0
5.0%
90.0%
5.0%
16.9%
80.3%
2.8%
@RISK Course Version
University of Canterbury
Input
Minimum 14.00
Maximum 327.00
Mean 75.83
Std Dev 49.85
Values 255
Normal
Minimum −∞
Maximum +∞
Mean 75.83
Std Dev 49.85


Fit Comparison for Unisys West
RiskNormal(90.109,65.296)
30.0
227.0
5.0%
90.0%
5.0%
17.9%
80.3%
1.8%
@RISK Course Version
University of Canterbury
Input
Minimum 9.00
Maximum 385.00
Mean 90.11
Std Dev 65.30
Values 312
Normal
Minimum −∞
Maximum +∞
Mean 90.11
Std Dev 65.30



Fit Comparison for Christchurch A
RiskNormal(57.961,23.861)
33.0
105.0
5.0%
90.0%
5.0%
14.8%
82.8%
2.4%
@RISK Course Version
University of Canterbury
Input
Minimum 20.00
Maximum 151.00
Mean 57.96
Std Dev 23.86
Values 103
Normal
Minimum -∞
Maximum +∞
Mean 57.96
Std Dev 23.86



Fit Comparison for Christchurch B
RiskNormal(66.871,35.099)
27.0
142.0
5.0%
90.0%
5.0%
12.8%
85.6%
1.6%
@RISK Course Version
University of Canterbury
Input
Minimum 0.00
Maximum 183.00
Mean 66.87
Std Dev 35.10
Values 139
Normal
Minimum -∞
Maximum +∞
Mean 66.87
Std Dev 35.10

Appendix II - Inputs

Typical ENZ Input files

Input files for all other stairs follow the same format.

```xml
<!-- Majestic Building Scenario File Library -->

  <!-- Majestic Simple layout -->
      <!-- Main Stair -->
<Scenario exists='enz_false'>D:\Masters Thesis\EvacuatioNZ Model\Majestic\Main stair\majmain_level1.xml</Scenario>
<Scenario exists='enz_false'>D:\Masters Thesis\EvacuatioNZ Model\Majestic\Main stair\majmain_level2.xml</Scenario>
<Scenario exists='enz_false'>D:\Masters Thesis\EvacuatioNZ Model\Majestic\Main stair\majmain_level3.xml</Scenario>

      <!-- Basement Stair -->
<Scenario exists='enz_false'>D:\Masters Thesis\EvacuatioNZ Model\Majestic\Basement stair\majbase_level1.xml</Scenario>
<Scenario exists='enz_false'>D:\Masters Thesis\EvacuatioNZ Model\Majestic\Basement stair\majbase_level2.xml</Scenario>
<Scenario exists='enz_false'>D:\Masters Thesis\EvacuatioNZ Model\Majestic\Basement stair\majbase_level3.xml</Scenario>

  <!-- Majestic Complex A layout -->
      <!-- Main Stair -->
<Scenario exists='enz_false'>D:\Masters Thesis\EvacuatioNZ Model\Majestic - Abstract\Main stair\majmainA_level1.xml</Scenario>
<Scenario exists='enz_false'>D:\Masters Thesis\EvacuatioNZ Model\Majestic - Abstract\Main stair\majmainA_level2.xml</Scenario>
<Scenario exists='enz_false'>D:\Masters Thesis\EvacuatioNZ Model\Majestic - Abstract\Main stair\majmainA_level3.xml</Scenario>

      <!-- Basement Stair -->
<Scenario exists='enz_false'>D:\Masters Thesis\EvacuatioNZ Model\Majestic - Abstract\Basement stair\majbaseA_level1.xml</Scenario>
<Scenario exists='enz_false'>D:\Masters Thesis\EvacuatioNZ Model\Majestic - Abstract\Basement stair\majbaseA_level2.xml</Scenario>
<Scenario exists='enz_false'>D:\Masters Thesis\EvacuatioNZ Model\Majestic - Abstract\Basement stair\majbaseA_level3.xml</Scenario>

<!-- Majestic Complex B layout -->
      <!-- Main Stair -->
<Scenario exists='enz_false'>D:\Masters Thesis\EvacuatioNZ Model\Majestic - Realistic\Main stair\majmainR_level1.xml</Scenario>
<Scenario exists='enz_false'>D:\Masters Thesis\EvacuatioNZ Model\Majestic - Realistic\Main stair\majmainR_level2.xml</Scenario>
<Scenario exists='enz_false'>D:\Masters Thesis\EvacuatioNZ Model\Majestic - Realistic\Main stair\majmainR_level3.xml</Scenario>

      <!-- Basement Stair -->
<Scenario exists='enz_false'>D:\Masters Thesis\EvacuatioNZ Model\Majestic - Realistic\Basement stair\majbaseR_level1.xml</Scenario>
<Scenario exists='enz_false'>D:\Masters Thesis\EvacuatioNZ Model\Majestic - Realistic\Basement stair\majbaseR_level2.xml</Scenario>
<Scenario exists='enz_true'>D:\Masters Thesis\EvacuatioNZ Model\Majestic - Realistic\Basement stair\majbaseR_level3.xml</Scenario>

<!-- Unisys Building Scenario File Library -->
```

Figure II - 2: Project XML file Showing Majestic Building Simulation Selection

```xml
<!-- Majestic Main stair  layout - Level 1 full random  -->

<EvacuatioNZ_Scenario version='2.00'>

  <Simulations>200</Simulations>
  <Convergence>0.0005</Convergence>

    <Files root="D:\Masters Thesis\EvacuatioNZ Model\Majestic\Main stair">

    <!-- Common input files -->
    <PersonType>%ROOT%\person_typemaj_level1.xml</PersonType>
    <Populate>%ROOT%\populatemaj_level1.xml</Populate>
    <Map>%ROOT%\majmain.graphml</Map>
       <!-- ExitBehaviour>%ROOT%exit_behaviour.xml</ExitBehaviour-->

    <!-- Case specific input files -->
    <Simulation>%ROOT%\simulationmaj_TS05.xml</Simulation>

    <!-- Output Files -->
  <PreEvacuation output='enz_true'>%ROOT%\output1\pre_evac.csv</PreEvacuation>
    <Evacuation output='enz_true'>%ROOT%\output1\evac.csv</Evacuation>
     <Nodes output='enz_true' minmax='enz_true'>%ROOT%\output1\nodes.csv</Nodes>
    <Connections output='enz_true'>%ROOT%\output1\connections.csv</Connections>
    <Actions output='enz_true'>%ROOT%\output1\actions.csv</Actions>
     <LogPath output='enz_true'>%ROOT%\output1\logpath\</LogPath>
    <Occupants output='enz_true'>%ROOT%\output1\occupants.csv</Occupants>

    </Files>

  </EvacuatioNZ_Scenario>
```

Figure II - 3: Scenario XML File; Majestic Main Stair Variation Level 1

Scenario files for each stair and for each variable had the exact same layout, the callouts changed based on folder and naming structures.

```xml
<!-- Majestic Main stair Complex A layout - persontype Variation level 1 (full random) -->

<EvacuatioNZ_PersonType version="2.00">

  <PersonTypeDefinition>
    <Name>adult</Name>
    <Speed>1.2</Speed><StartDistance type="enz_minimum"/>
        <ExitBehaviour>default</ExitBehaviour>
        <PreEvacuation type='enz_distribution'>
                <Distribution type='enz_normal'>
                    <Mean>94</Mean>
                    <StandardDeviation>48</StandardDeviation>
                </Distribution>
            </PreEvacuation>
    </PersonTypeDefinition>
```

```xml
<!-- Majestic Main stair Complex A layout - persontype Variation level 2 -->

<EvacuatioNZ_PersonType version="2.00">

  <PersonTypeDefinition>
    <Name>adult</Name>
    <Speed>1.2</Speed><StartDistance type="enz_minimum"/>
        <ExitBehaviour>default</ExitBehaviour>
        <PreEvacuation type='enz_distribution'>
                <Distribution type='enz_normal'>
                    <Mean>94</Mean>
                    <StandardDeviation>48</StandardDeviation>
                </Distribution>
            </PreEvacuation>
    </PersonTypeDefinition>


    </EvacuatioNZ_PersonType>
```

```xml
<!--  Majestic Main stair Complex A layout - persontype Variation level 3 -->

<EvacuatioNZ_PersonType version="2.00">

  <!-- Assigned premovement -->

  <PersonTypeDefinition><Name>adult1</Name><Speed>1.2</Speed><StartDistance type="enz_minimum"/><ExitBehaviour>default</ExitBehaviour><PreEvacuation>38</PreEvacuation><
<PersonTypeDefinition><Name>adult2</Name><Speed>1.2</Speed><StartDistance type="enz_minimum"/><ExitBehaviour>default</ExitBehaviour><PreEvacuation>39</PreEvacuation></
<PersonTypeDefinition><Name>adult3</Name><Speed>1.2</Speed><StartDistance type="enz_minimum"/><ExitBehaviour>default</ExitBehaviour><PreEvacuation>41</PreEvacuation></
<PersonTypeDefinition><Name>adult4</Name><Speed>1.2</Speed><StartDistance type="enz_minimum"/><ExitBehaviour>default</ExitBehaviour><PreEvacuation>43</PreEvacuation></
<PersonTypeDefinition><Name>adult5</Name><Speed>1.2</Speed><StartDistance type="enz_minimum"/><ExitBehaviour>default</ExitBehaviour><PreEvacuation>45</PreEvacuation></
<PersonTypeDefinition><Name>adult6</Name><Speed>1.2</Speed><StartDistance type="enz_minimum"/><ExitBehaviour>default</ExitBehaviour><PreEvacuation>47</PreEvacuation></
<PersonTypeDefinition><Name>adult7</Name><Speed>1.2</Speed><StartDistance type="enz_minimum"/><ExitBehaviour>default</ExitBehaviour><PreEvacuation>54</PreEvacuation></
<PersonTypeDefinition><Name>adult8</Name><Speed>1.2</Speed><StartDistance type="enz_minimum"/><ExitBehaviour>default</ExitBehaviour><PreEvacuation>55</PreEvacuation></
<PersonTypeDefinition><Name>adult9</Name><Speed>1.2</Speed><StartDistance type="enz_minimum"/><ExitBehaviour>default</ExitBehaviour><PreEvacuation>59</PreEvacuation></
<PersonTypeDefinition><Name>adult10</Name><Speed>1.2</Speed><StartDistance type="enz_minimum"/><ExitBehaviour>default</ExitBehaviour><PreEvacuation>62</PreEvacuation><
<PersonTypeDefinition><Name>adult11</Name><Speed>1.2</Speed><StartDistance type="enz_minimum"/><ExitBehaviour>default</ExitBehaviour><PreEvacuation>64</PreEvacuation><
<PersonTypeDefinition><Name>adult12</Name><Speed>1.2</Speed><StartDistance type="enz_minimum"/><ExitBehaviour>default</ExitBehaviour><PreEvacuation>66</PreEvacuation><
<PersonTypeDefinition><Name>adult13</Name><Speed>1.2</Speed><StartDistance type="enz_minimum"/><ExitBehaviour>default</ExitBehaviour><PreEvacuation>67</PreEvacuation><
<PersonTypeDefinition><Name>adult14</Name><Speed>1.2</Speed><StartDistance type="enz_minimum"/><ExitBehaviour>default</ExitBehaviour><PreEvacuation>68</PreEvacuation><
<PersonTypeDefinition><Name>adult15</Name><Speed>1.2</Speed><StartDistance type="enz_minimum"/><ExitBehaviour>default</ExitBehaviour><PreEvacuation>69</PreEvacuation><
<PersonTypeDefinition><Name>adult16</Name><Speed>1.2</Speed><StartDistance type="enz_minimum"/><ExitBehaviour>default</ExitBehaviour><PreEvacuation>70</PreEvacuation><
<PersonTypeDefinition><Name>adult17</Name><Speed>1.2</Speed><StartDistance type="enz_minimum"/><ExitBehaviour>default</ExitBehaviour><PreEvacuation>71</PreEvacuation><
<PersonTypeDefinition><Name>adult18</Name><Speed>1.2</Speed><StartDistance type="enz_minimum"/><ExitBehaviour>default</ExitBehaviour><PreEvacuation>76.0000000000001</Pr
<PersonTypeDefinition><Name>adult19</Name><Speed>1.2</Speed><StartDistance type="enz_minimum"/><ExitBehaviour>default</ExitBehaviour><PreEvacuation>168</PreEvacuation><
```


Figure II - 4: Persontype XML Files; Variation 1, 2 and 3

```xml
<!-- Majestic Main stair Complex A layout - populate Variation level 1 -->

 <EvacuatioNZ_Populate version="2.00">

    <PopulationDefinition>
        <People>377</People>
        <Log>no</Log>
        <Node type="enz_spread" refstyle="enz_name">Level 4,Level 5,Level 6,Level 7,Level 8,Level 9,Level 10,Level 11,Level 12,Level 13,L
        <PersonType>
            <Name>adult</Name>
            <Probability>100</Probability>
            </PersonType>
    </PopulationDefinition>

        </EvacuatioNZ_Populate>
```

```xml
<!-- Majestic Main stair Complex A layout - populate Variation level 2 -->

 <EvacuatioNZ_Populate version="2.00">

    <PopulationDefinition>
        <People>21</People>
        <Log>no</Log>
        <Node type="enz_single" refstyle="enz_name">Level 4</Node>
        <PersonType>
            <Name>adult</Name>
            <Probability>100</Probability>
            </PersonType>
    </PopulationDefinition>

    <PopulationDefinition>
            <People>30</People>
            <Log>no</Log>
            <Node type="enz_single" refstyle="enz_name">Level 5</Node>
        <PersonType>
            <Name>adult</Name>
            <Probability>100</Probability>
            </PersonType>
    </PopulationDefinition>


        <PopulationDefinition>
        <People>33</People>
        <Log>no</Log>
```

```xml
<!-- Majestic Main stair Complex A layout - populate Variation level 3 -->

<EvacuatioNZ_Populate version="2.00">

    <PopulationDefinition><People>1</People><Log>no</Log><Node type='enz_single' refstyle='enz_name'>Level 4</Node><PersonType><Name>adult1</Name><Proba
<PopulationDefinition><People>1</People><Log>no</Log><Node type='enz_single' refstyle='enz_name'>Level 4</Node><PersonType><Name>adult2</Name><Probabili
<PopulationDefinition><People>1</People><Log>no</Log><Node type='enz_single' refstyle='enz_name'>Level 4</Node><PersonType><Name>adult3</Name><Probabili
<PopulationDefinition><People>1</People><Log>no</Log><Node type='enz_single' refstyle='enz_name'>Level 4</Node><PersonType><Name>adult4</Name><Probabili
<PopulationDefinition><People>1</People><Log>no</Log><Node type='enz_single' refstyle='enz_name'>Level 4</Node><PersonType><Name>adult5</Name><Probabili
<PopulationDefinition><People>1</People><Log>no</Log><Node type='enz_single' refstyle='enz_name'>Level 4</Node><PersonType><Name>adult6</Name><Probabili
<PopulationDefinition><People>1</People><Log>no</Log><Node type='enz_single' refstyle='enz_name'>Level 4</Node><PersonType><Name>adult7</Name><Probabili
<PopulationDefinition><People>1</People><Log>no</Log><Node type='enz_single' refstyle='enz_name'>Level 4</Node><PersonType><Name>adult8</Name><Probabili
<PopulationDefinition><People>1</People><Log>no</Log><Node type='enz_single' refstyle='enz_name'>Level 4</Node><PersonType><Name>adult9</Name><Probabili
<PopulationDefinition><People>1</People><Log>no</Log><Node type='enz_single' refstyle='enz_name'>Level 4</Node><PersonType><Name>adult10</Name><Probabil
<PopulationDefinition><People>1</People><Log>no</Log><Node type='enz_single' refstyle='enz_name'>Level 4</Node><PersonType><Name>adult11</Name><Probabil
<PopulationDefinition><People>1</People><Log>no</Log><Node type='enz_single' refstyle='enz_name'>Level 4</Node><PersonType><Name>adult12</Name><Probabil
<PopulationDefinition><People>1</People><Log>no</Log><Node type='enz_single' refstyle='enz_name'>Level 4</Node><PersonType><Name>adult13</Name><Probabil
<PopulationDefinition><People>1</People><Log>no</Log><Node type='enz_single' refstyle='enz_name'>Level 4</Node><PersonType><Name>adult14</Name><Probabil
<PopulationDefinition><People>1</People><Log>no</Log><Node type='enz_single' refstyle='enz_name'>Level 4</Node><PersonType><Name>adult15</Name><Probabil
<PopulationDefinition><People>1</People><Log>no</Log><Node type='enz_single' refstyle='enz_name'>Level 4</Node><PersonType><Name>adult16</Name><Probabil
<PopulationDefinition><People>1</People><Log>no</Log><Node type='enz_single' refstyle='enz_name'>Level 4</Node><PersonType><Name>adult17</Name><Probabil
<PopulationDefinition><People>1</People><Log>no</Log><Node type='enz_single' refstyle='enz_name'>Level 4</Node><PersonType><Name>adult18</Name><Probabil
<PopulationDefinition><People>1</People><Log>no</Log><Node type='enz_single' refstyle='enz_name'>Level 4</Node><PersonType><Name>adult19</Name><Probabil
<PopulationDefinition><People>1</People><Log>no</Log><Node type='enz_single' refstyle='enz_name'>Level 4</Node><PersonType><Name>adult20</Name><Probabil
<PopulationDefinition><People>1</People><Log>no</Log><Node type='enz_single' refstyle='enz_name'>Level 4</Node><PersonType><Name>adult21</Name><Probabil
<PopulationDefinition><People>1</People><Log>no</Log><Node type='enz_single' refstyle='enz_name'>Level 5</Node><PersonType><Name>adult22</Name><Probabil
<PopulationDefinition><People>1</People><Log>no</Log><Node type='enz_single' refstyle='enz_name'>Level 5</Node><PersonType><Name>adult23</Name><Probabil
<PopulationDefinition><People>1</People><Log>no</Log><Node type='enz_single' refstyle='enz_name'>Level 5</Node><PersonType><Name>adult24</Name><Probabil
<PopulationDefinition><People>1</People><Log>no</Log><Node type='enz_single' refstyle='enz_name'>Level 5</Node><PersonType><Name>adult25</Name><Probabil
<PopulationDefinition><People>1</People><Log>no</Log><Node type='enz_single' refstyle='enz_name'>Level 5</Node><PersonType><Name>adult26</Name><Probabil
<PopulationDefinition><People>1</People><Log>no</Log><Node type='enz_single' refstyle='enz_name'>Level 5</Node><PersonType><Name>adult27</Name><Probabil
```


Figure II - 5: Populate XML Files; Variation Type 1, 2 and 3

```xml
<!-- Manchester Building Clean Complex layout A -->

<EvacuatioNZ_Simulation version='2.00'>

    <TimeMax>800</TimeMax>
    <TimeStep>0.5</TimeStep>


  <!-- No specific flow defined so default value is used, 1.33 ppl/meff/s -->

</EvacuatioNZ_Simulation>
```

Figure II - 6: Simulation XML File

Simulation files are exactly the same for all stairs and all variables, the only change was to the "TimeStep" entry, which is either 1.0, 0.5 or 0.1 during sensitivity analysis.

Typical ENZ Graphml Layout for Stairs

Example layouts depict how layouts were set up for all stairs and the only variable was the dimensions for certain elements. Chapter 2 will contain details for these inputs.

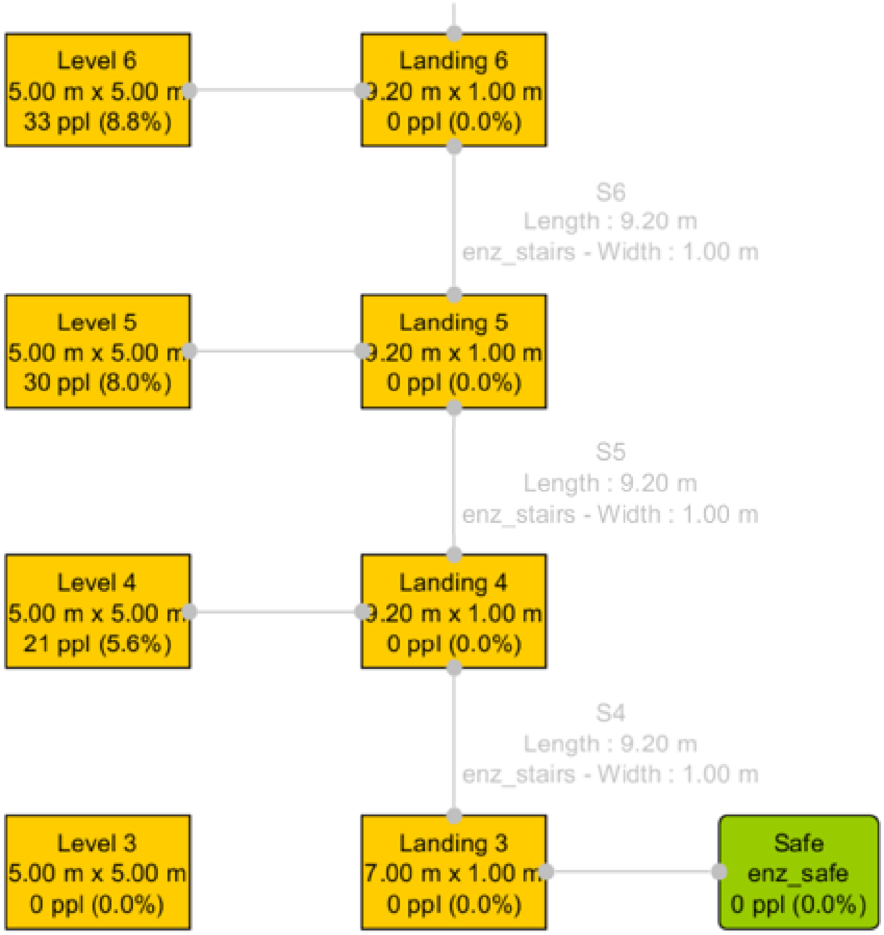


Figure II - 7: Example of Simple Stair Layout in Graphml

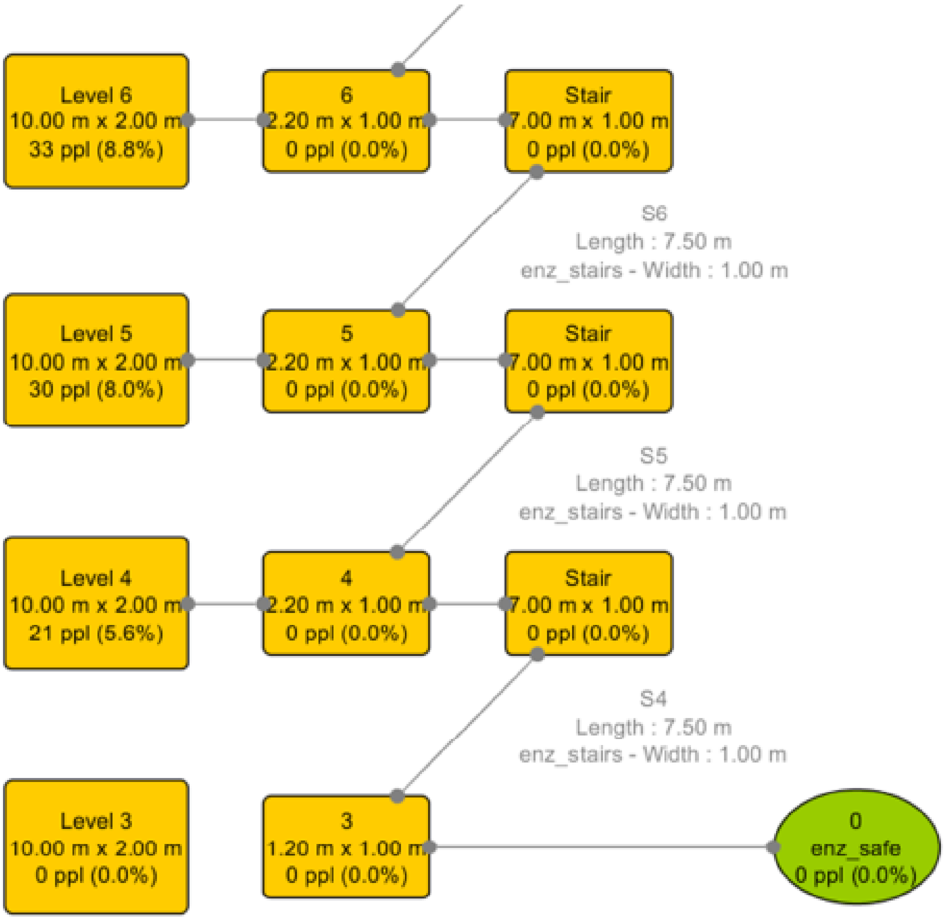


Figure II - 8: Example of Complex A Stair Layout in Graphml

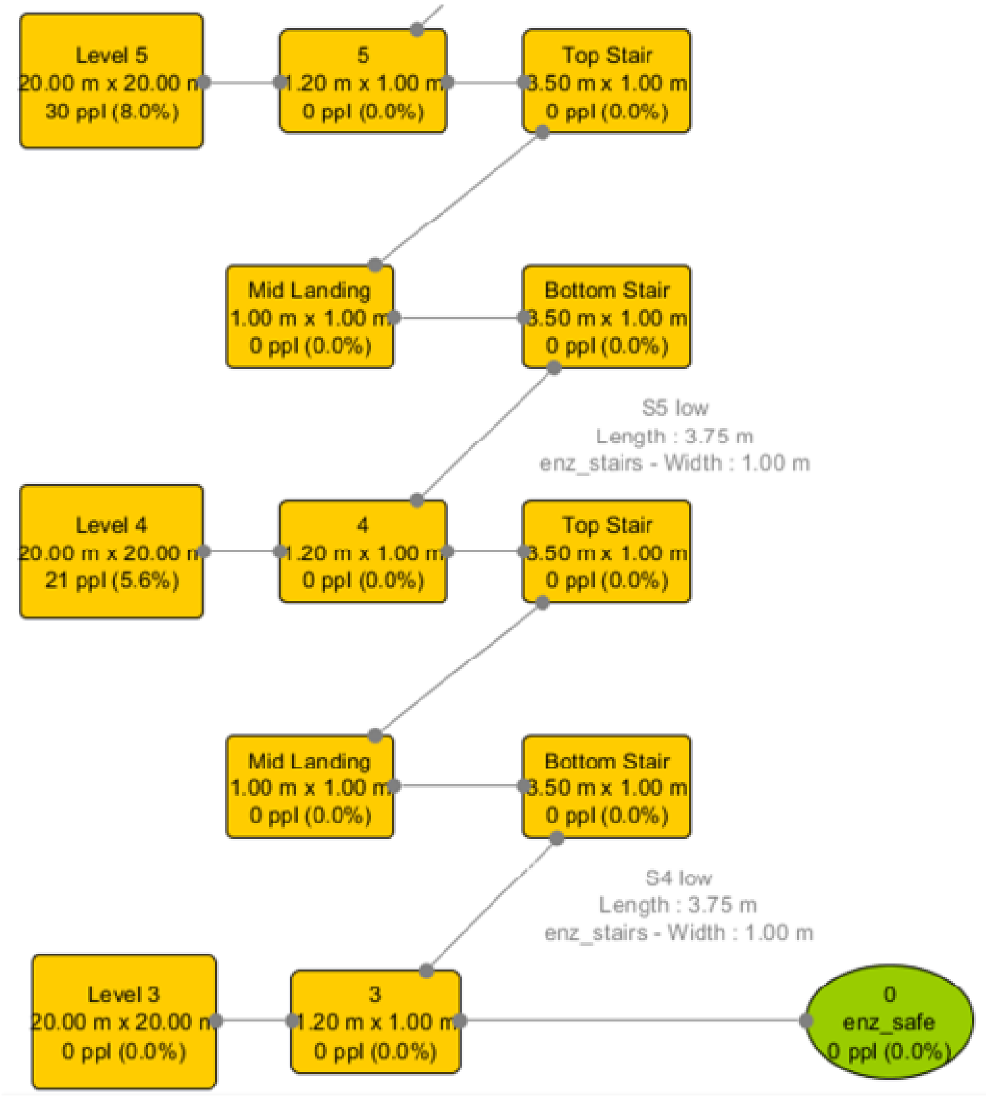


Figure II - 9: Example of Complex B Stair Layout in Graphml

Appendix III – Analysis

Figure III - 1: Additional Case Study Building/Stair Information Summary

Building	Stair	Stair Width (m)	Building Height (m)	Population	Average Pop/Floor	Stair Entry Average ± Std Dev (sec)	Total Egress Time ± Std Dev (sec)
Manchester	Clean Stair	0.95	17	168	10	77.1 ± 31.8	351
	Dirty Stair	0.98	17	79	5	63.5 ±21	321
Majestic	Main Stair	1.0	23	377	17	93.7 ±48.2	583
	Basement Stair	1.0	27	302	12	101.1 ±40.2	637
Unisys	East Stair	1.05	17	255	15	75.8 ±49.9	531
	West Stair	1.05	17	312	19	90.1 ±65	542
Christchurch	Stair A	1.02	11	103	10	58 ±23.9	216
	Stair B	1.02	11	137	13	68.4	301

Time Step	Main Stair averages (sec)			Basement Stair averages (sec)		
	Level 1	Level 2	Level 3	Level 1	Level 2	Level 3
1 sec	648	646	640	619	636	635
0.5 sec	601	597	584	582	593	591
0.1 sec	583	578	572	557	572	589
Case Study	583 seconds			637 seconds		

Figure III - 2: Majestic Time Step Analysis

Time Step	Clean stair averages (sec)		Dirty stair averages (sec)	
	Level 1	Level 2	Level 1	Level 2
1 sec	395	401	344	372
0.5 sec	365	372	314	334
0.1 sec	349	347	295	312
Case Study	427 seconds *351 seconds		321 seconds	

Figure III - 3: Manchester Time Step Analysis

Additional Graph Comparisons for EvacuatioNZ and Pauls' Hand Calculation

As discussed in 4.1.1 and described in Chapter 2, Manchester Clean stair's adjusted total egress time is 351 seconds. The excluded occupants are included in the graphical outputs for completeness, as the 351 second end point is easily distinguishable.

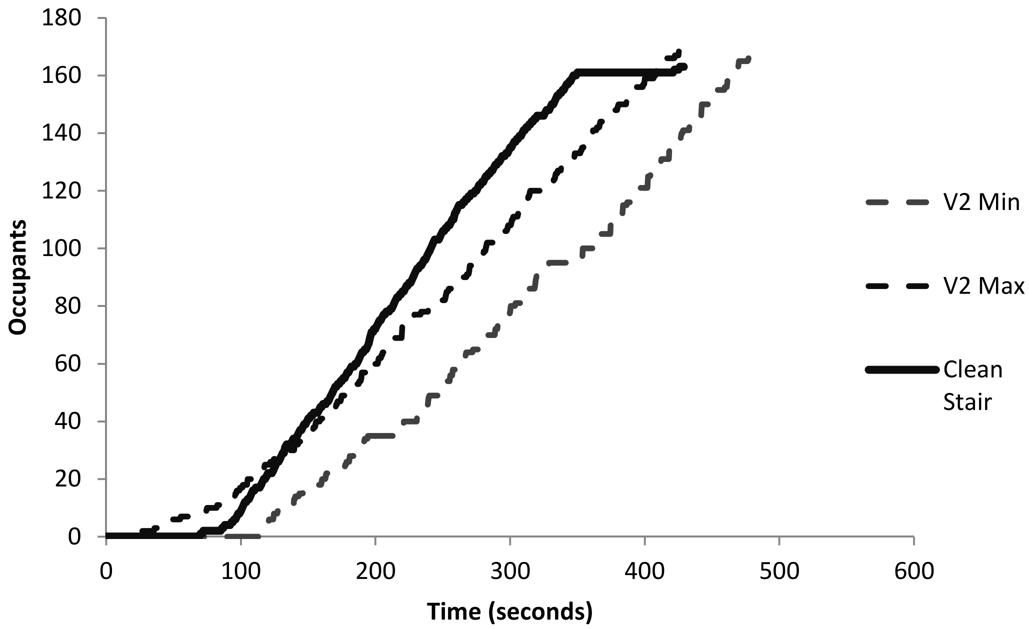


Figure III - 4: Manchester Clean Stair min-max Cumulative Plot Comparison with Case Study Results

The result of the Manchester Clean stair model is closer to the case study if the tail end occupants are included, although the model does not have any noticeable tail end (Figure III - 4). The case study average egress flow rate was estimated to be 0.61ppl/s. The model flow rate ranged from 0.46 to 0.57ppl/s, which is a slower flow rate compared to the case study.

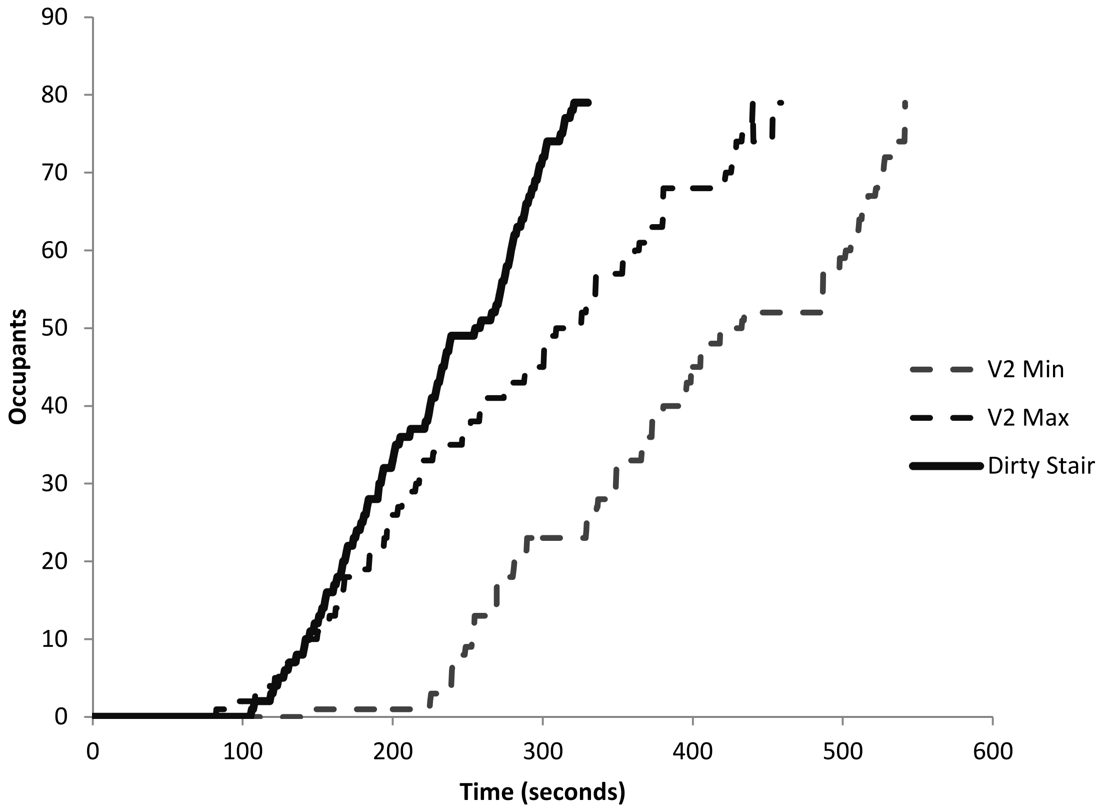


Figure III - 5: Manchester Dirty Stair min-max Cumulative Plot Comparison with Case Study Results

The Dirty stair model has similar first stair entry time, but has a much longer total egress time (Figure III - 5). The case study average egress flow rate was estimated to be 0.37ppl/s. The model has an estimated average flow rate of 0.23ppl/s. There are periods of slower or no flow in the model which mirrors the case study to an extent. This occurrence is more pronounced in the model's minimum curve result.

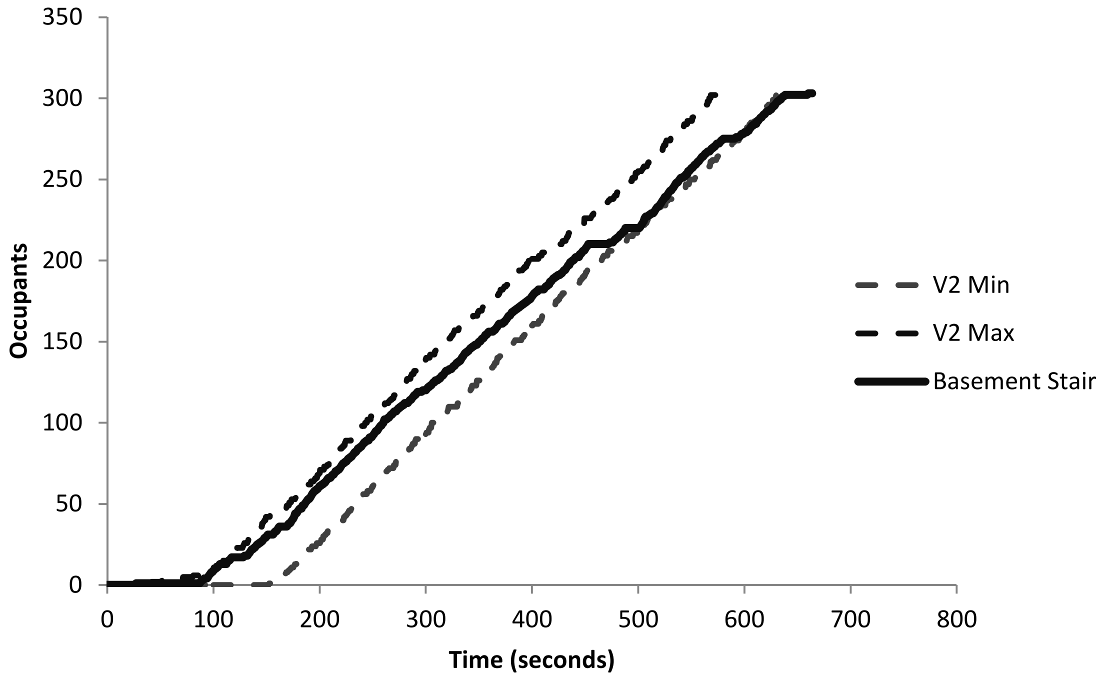


Figure III - 6: Majestic Basement Stair min-max Cumulative Plot Comparison with Case Study Results

The Basement model result falls on the non-conservative side of the case study data (Figure III - 6). The average egress flow rate for the case study data was estimated to be 0.56ppl/s. Model results ranged from 0.62 to 0.66ppl/s. The case study has a short period of slower egress flow rate, the same does not occur in the model results.

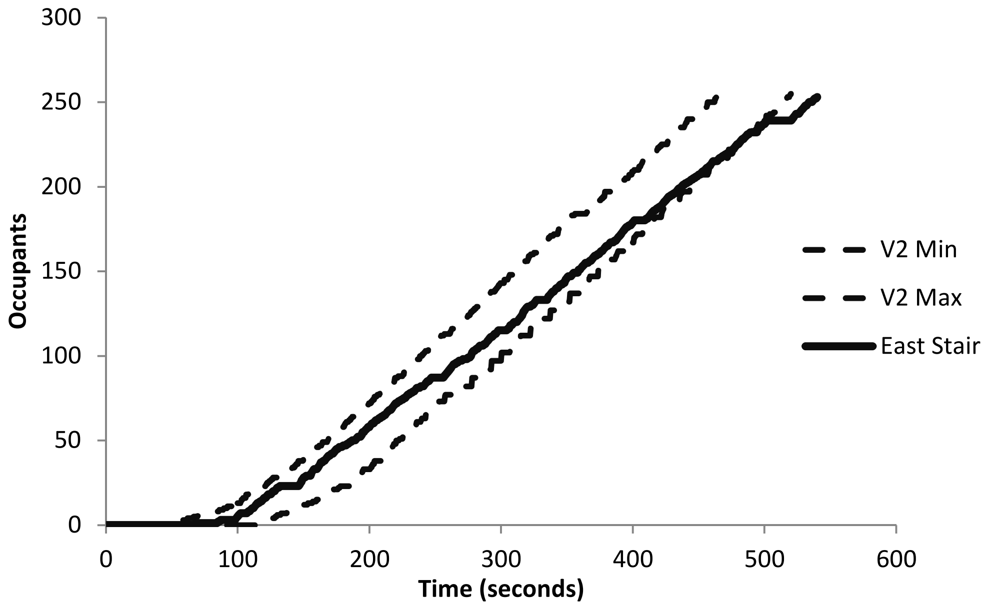


Figure III - 7: Unisys East Stair min-max Cumulative Plot Comparison with Case Study Results

The Unisys East stair model results range brackets the total egress time of the case study (Figure III - 7). The average egress flow rate for the case study was estimated to be 0.62ppl/s. While the model results were both approximately 0.68ppl/s. Egress flow rate in the case study slowed near the end of the evacuation, the same does not occur in the model results.

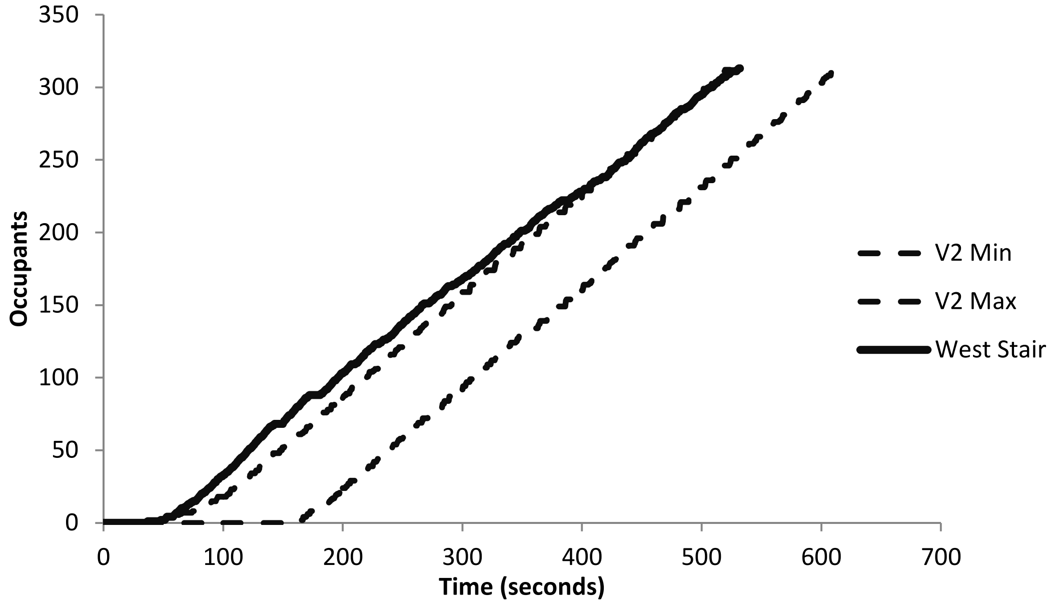


Figure III - 8: Unisys West Stair min-max Cumulative Plot Comparison with Case Study Results

Similarly to the East stair, the West stair model results range brackets the total egress time of the case study. The average egress flow rate for the case study was estimated to be 0.65ppl/s. The model results were both approximately 0.7ppl/s.

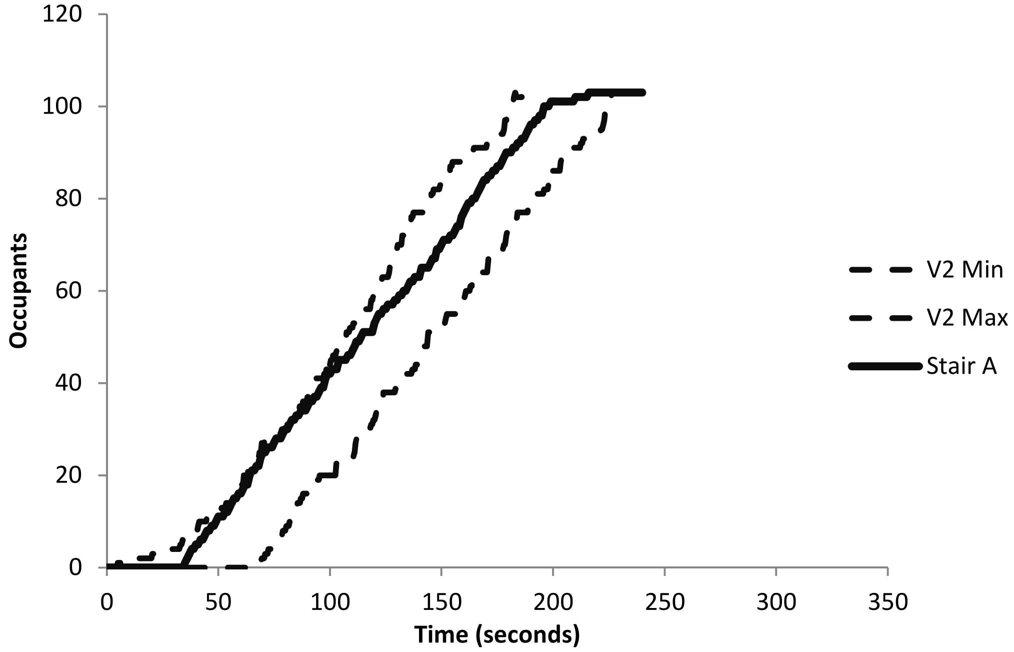


Figure III - 9: Christchurch Stair A min-max Cumulative Plot Comparison with Case Study Results

The results for Christchurch stair A model are similar to a non-tail end result for the case study (Figure III - 9). The average egress flow rate for the case study was estimated to be 0.62ppl/s. The estimated average model egress flow rate ranged from 0.63 to 0.68ppl/s

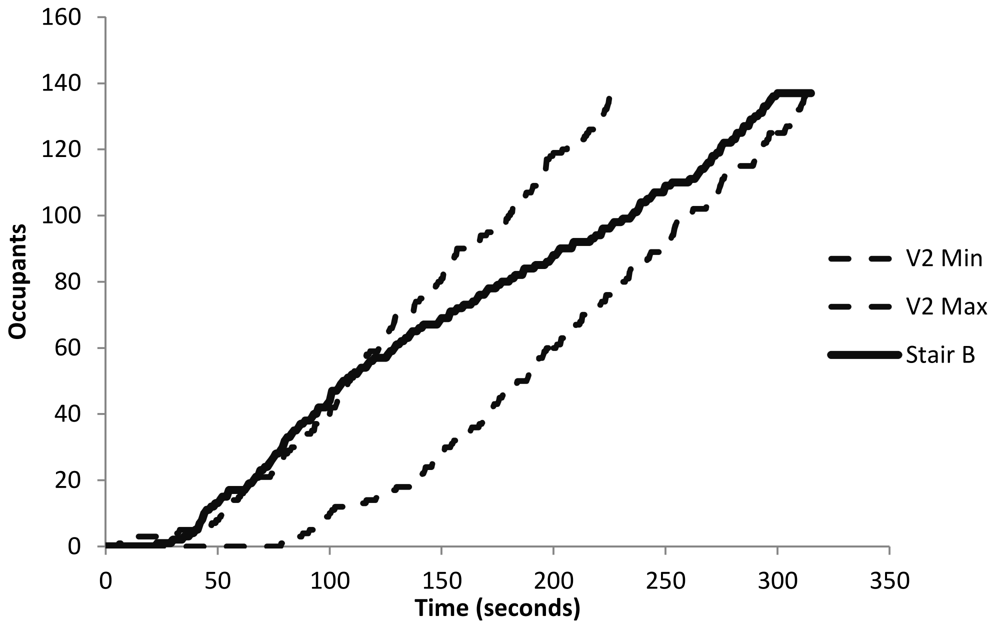


Figure III - 10: Christchurch Stair B min-max Cumulative Plot Comparison with Case Study Results

The results for the stair B model have a significant range, most of which is less conservative than the case study result (Figure III - 10). The average egress flow rate for the case study was estimated to be 0.49ppl/s. While the model ranged from 0.65 to 0.77ppl/s. The case study has a initial egress flow rate of approximately 0.75ppl/s but this slows down to the estimated 0.49ppl/s after around 100 seconds.

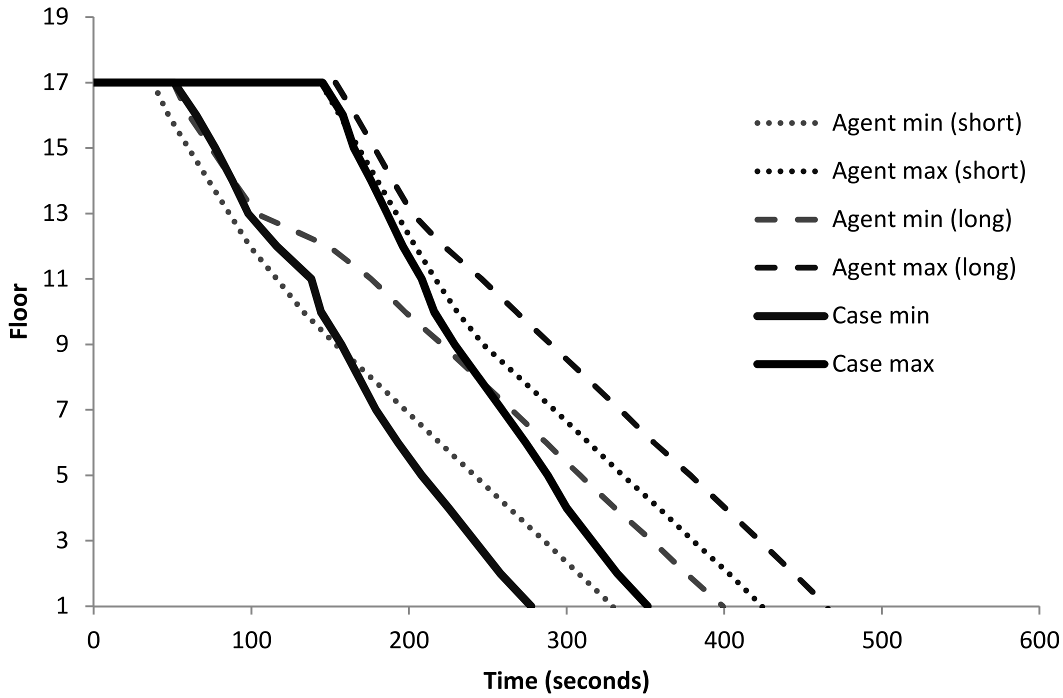


Figure III - 11: Manchester Clean Stair Descent Plot with Comparison to Case Study Occupants

The minimum stair entry time agents are close to the sampled case study occupants (Figure III - 11). The case study occupant speeds were estimated to be approximately 0.64 to 0.68m/s. Average agent speeds were estimated at 0.45m/s. Some agents started with a faster speed of 0.61m/s, slowing to 0.4m/s around floor 13.

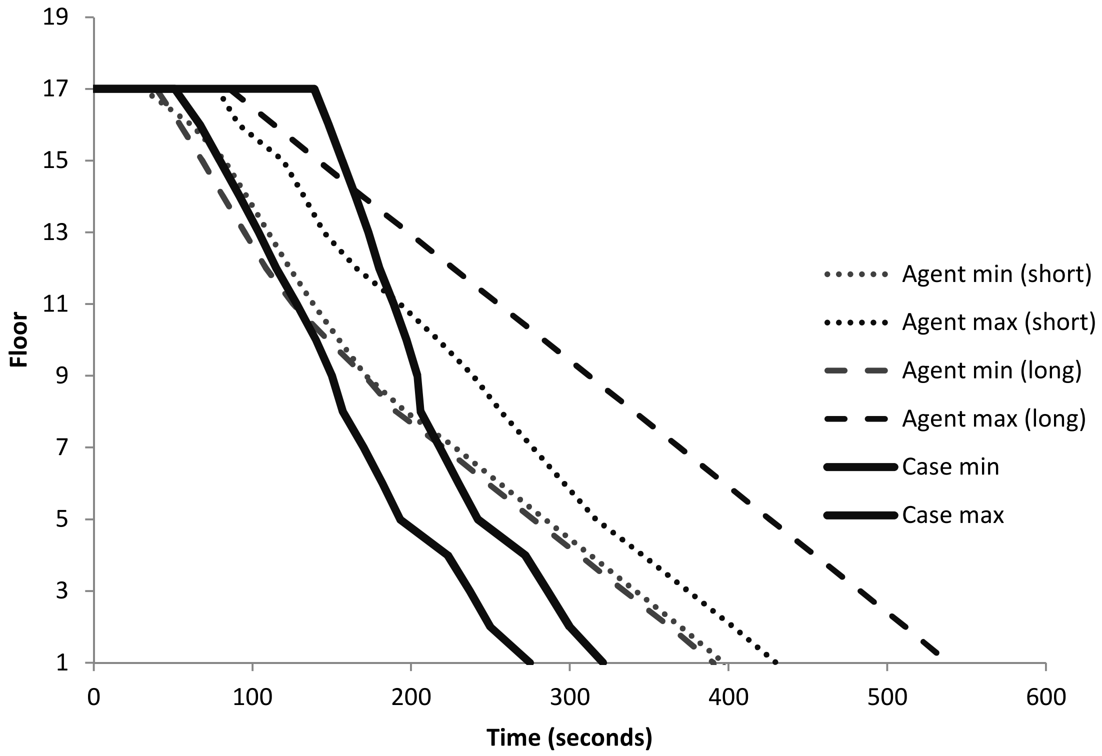


Figure III - 12: Manchester Dirty Stair Descent Plot with Comparison to Case Study Occupants

The agent stair entry times were close to one of the case study occupants (Figure III - 12) The case study occupant speeds were estimated to be approximately 0.39 to 0.71m/s. Most agents had an estimated speed of 0.33 to 0.43m/s. The minimum agent for the long simulation had a speed of 0.62m/s, slowing to 0.33m/s around floor 11. The agent with the greatest total egress time had a consistent speed of 0.32m/s.

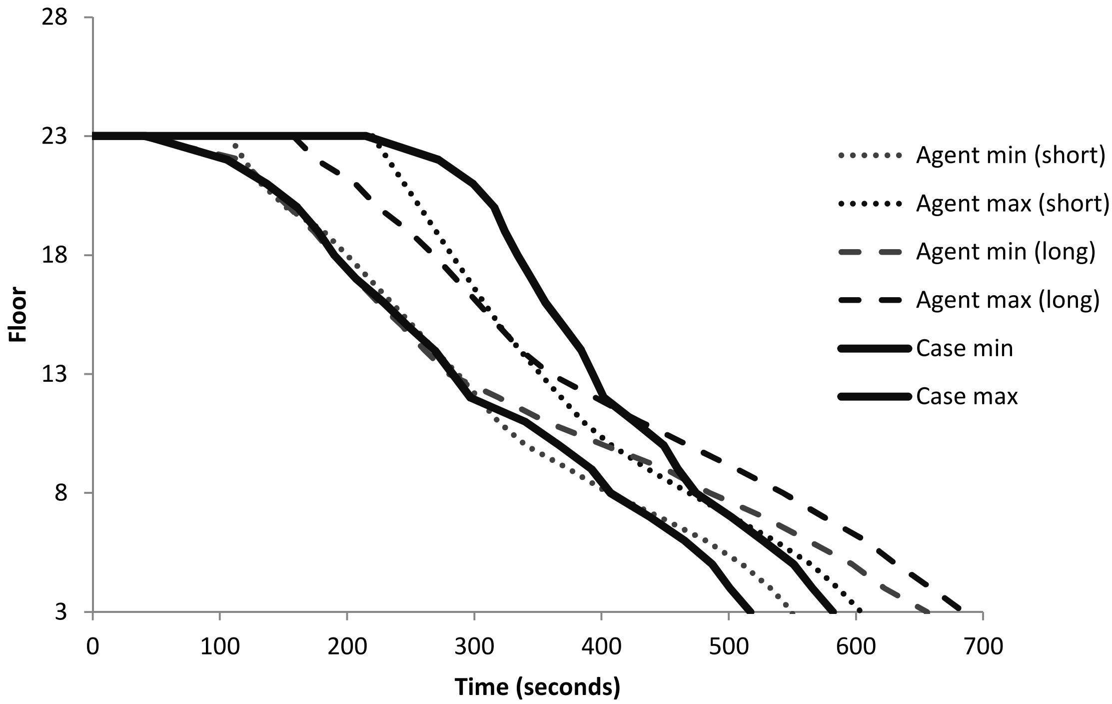


Figure III - 13: Majestic Main Stair Descent Plot with Comparison to Case Study Occupants

The agent stair entry times were within the range of the case study occupants (Figure III - 13). The case study occupant speeds were estimated to be approximately 0.41 to 0.63m/s. The model agents had estimated speeds of 0.58m/s, between floors 13 and 10, most agents slowed to speeds of approximately 0.31m/s.

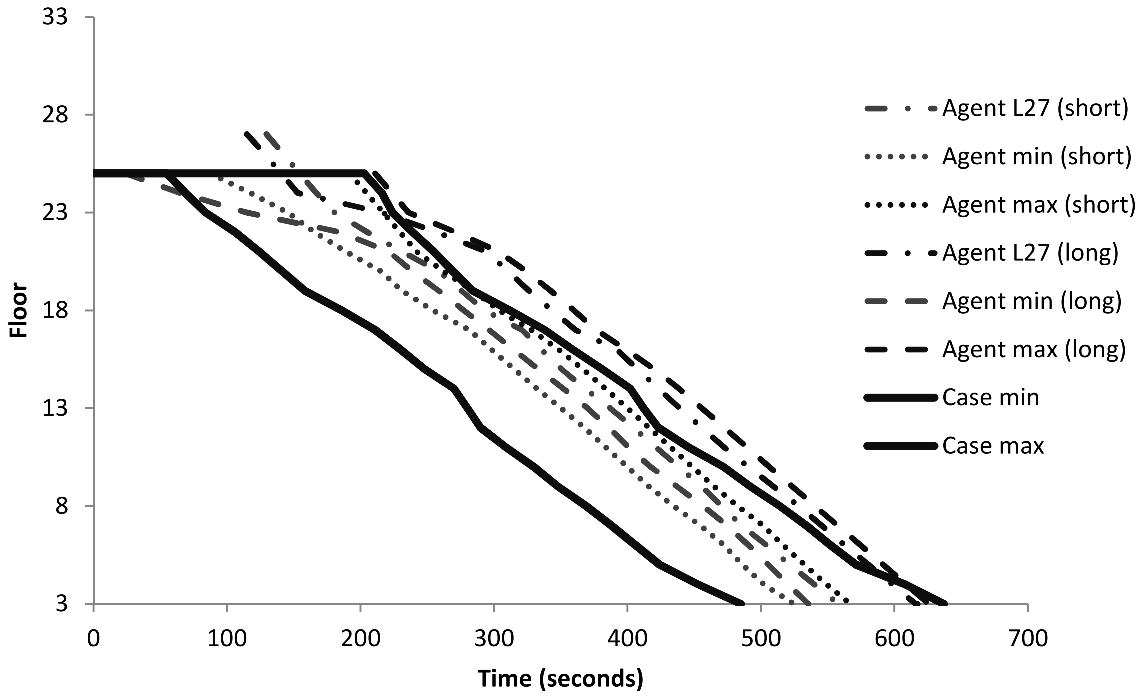


Figure III - 14: Majestic Basement Stair Descent Plot with Comparison to Case Study Occupants

The majority of model agent's stair entry times fall within the range of case study stair entry times (Figure III - 14). Both case study occupants had an estimated speed of approximately 0.63m/s. This speed excludes some periods of slower speeds. The model agents had estimated average speeds of 0.68m/s.

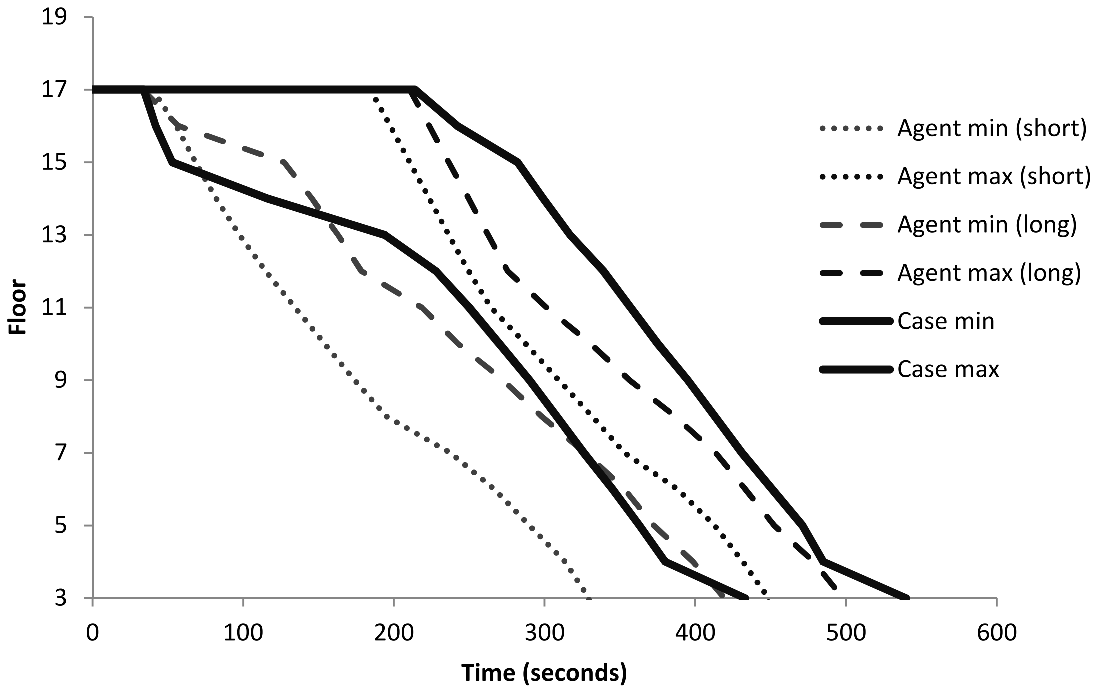


Figure III - 15: Unisys East Stair Descent Plot with Comparison to Case Study Occupants

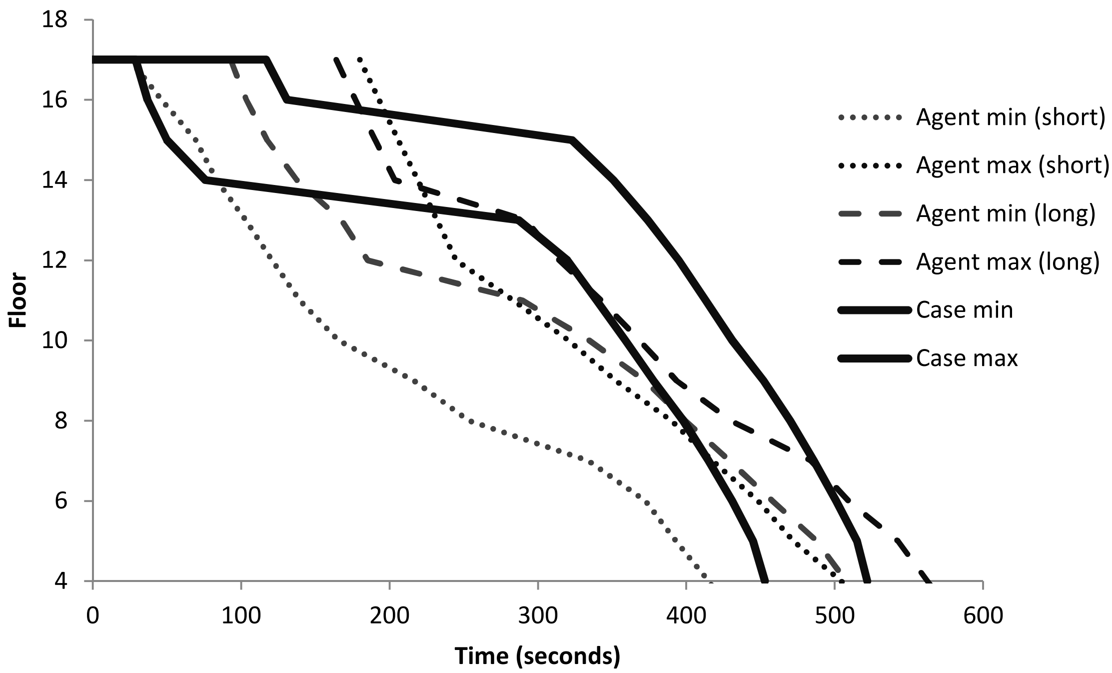


Figure III - 16: Unisys West Stair Descent Plot with Comparison to Case Study Occupants

The case study occupant's stair entry times have a smaller range than the model agent stair entry times (Figure III - 16). Both case study occupants experience a significant period (~3minutes), the model agents from the long simulation experience a slowdown period in a similar area but for about half the duration. Case study occupant descent speeds is estimated to be 0.45 to 0.47m/s before and after the slowdown period and the occupants is estimated to be moving 0.1m/s or less during the slowdown period. Model agents have estimated average speeds of 0.43m/s on the upper floors, which slows to approximately 0.26m/s on the lower floors.

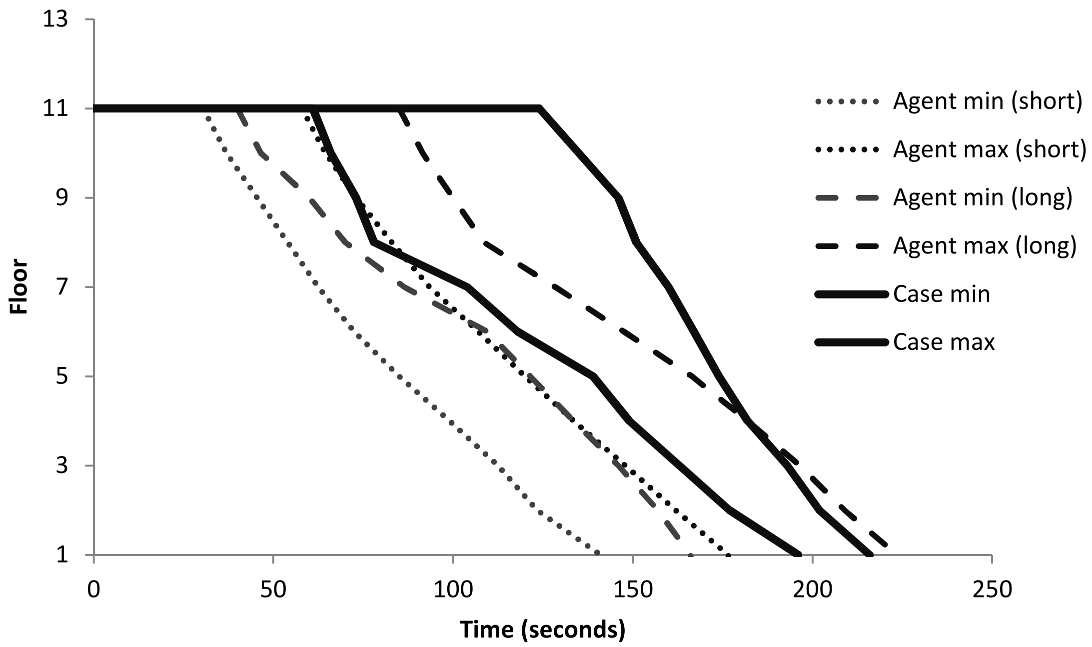


Figure III - 17: Christchurch Stair A Descent Plot with Comparison to Case Study Occupants

The model agents have stair entry times shorter than the case study occupants sampled (Figure III - 17). The case study occupant's speed is estimated to be 1.27m/s at the fastest, the minimum occupant slowed down to 0.49m/s after floor 8. The agents from the short simulation had average speeds of approximately 0.6m/s. Some agents had faster estimated speed of 0.94m/s, which slows to 0.41m/s around floor 8.

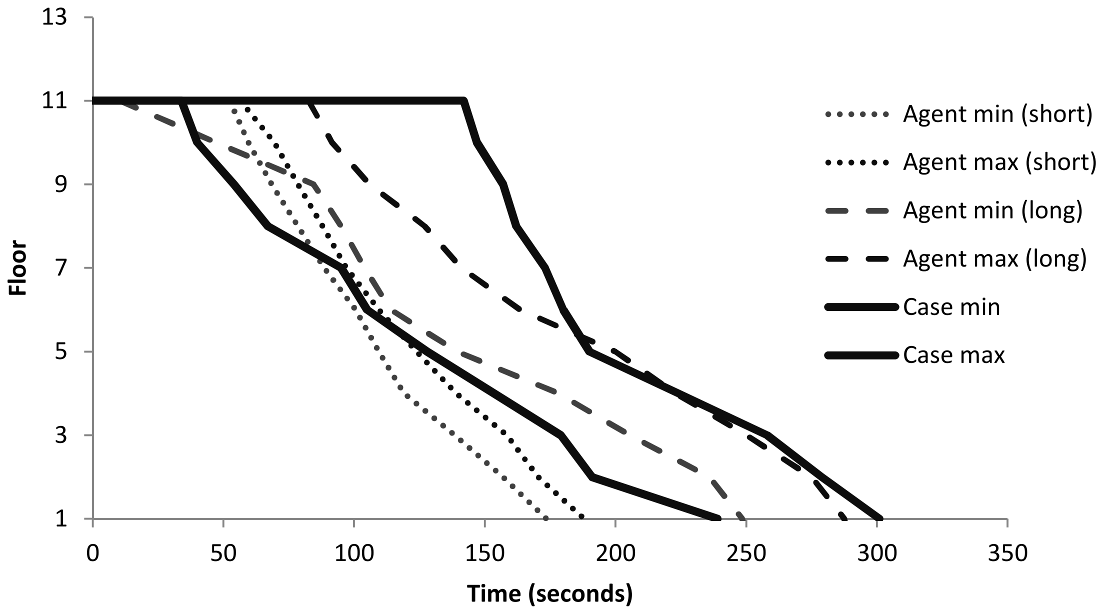


Figure III - 18: Christchurch Stair B Descent Plot with Comparison to Case Study Occupants

Model agent stair entry times are in general closer to the minimum agent (Figure III - 18). The case study occupants had an estimated speed of 0.9m/s on the upper floors, both slowed down to speeds of 0.22 to 0.35m/s. The short simulation agents had average estimated speeds of 0.55m/s. While, the long simulation agents have early descent speeds of approximately 0.3m/s, they slow to approximately 0.20m/s around floor 8 and 9.

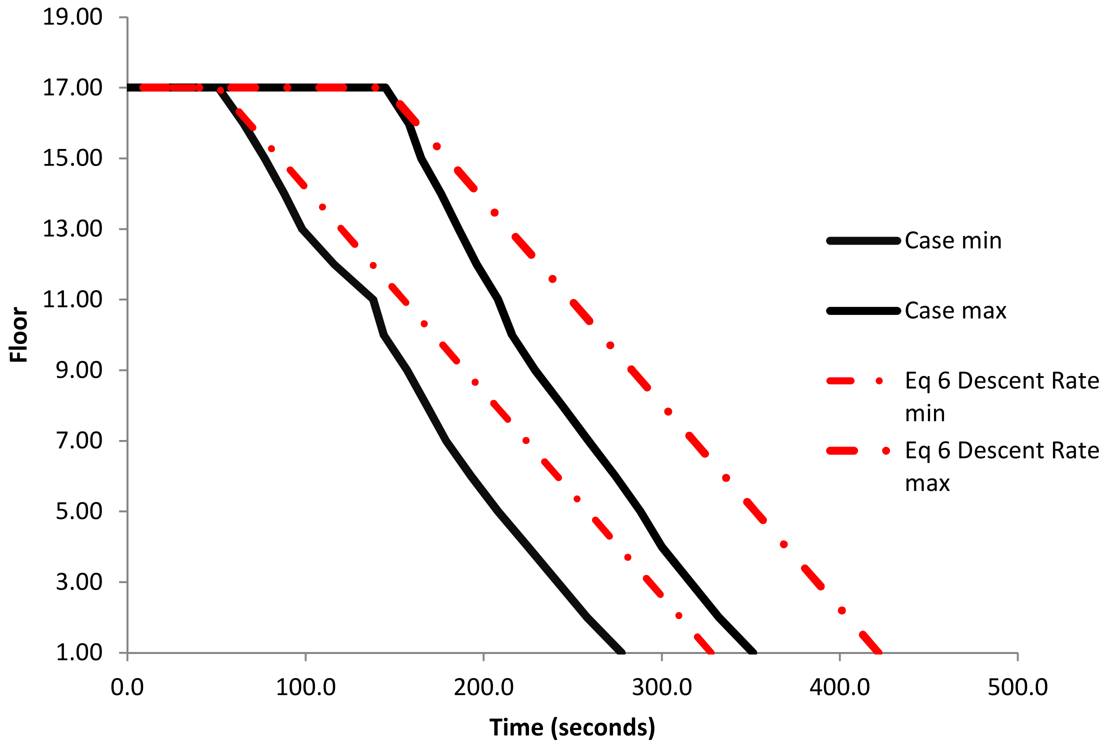


Figure III - 19: Manchester Clean Stair Case Study Occupants Compared with the Derived Descent Rate

The total egress time prediction of equation 6 using the Manchester Clean stair entry times are longer than the case study for both sampled occupants (Figure III - 19). The prediction line's speed of 0.51m/s is slower than the 0.64 – 0.68m/s range for the case study occupants.

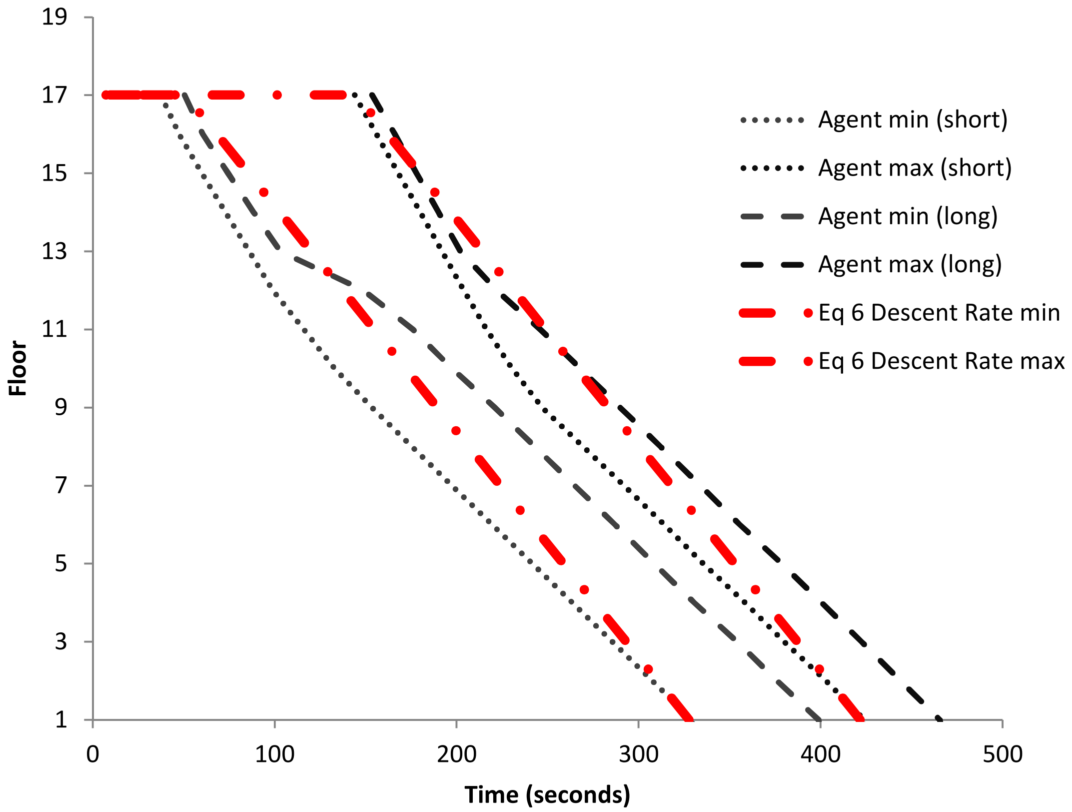


Figure III - 20: Manchester Clean Stair Model Simulation Agents Compared with the Derived Descent Rate

Comparing to the model results, the equation 6 predicted total egress time is quite close to many of the sampled agents (Figure III - 20). The stair entry times are also close. The prediction line's speed of 0.51m/s is within the range of estimated model agent speeds which begin at 0.67m/s and slow to 0.41 – 0.45m/s.

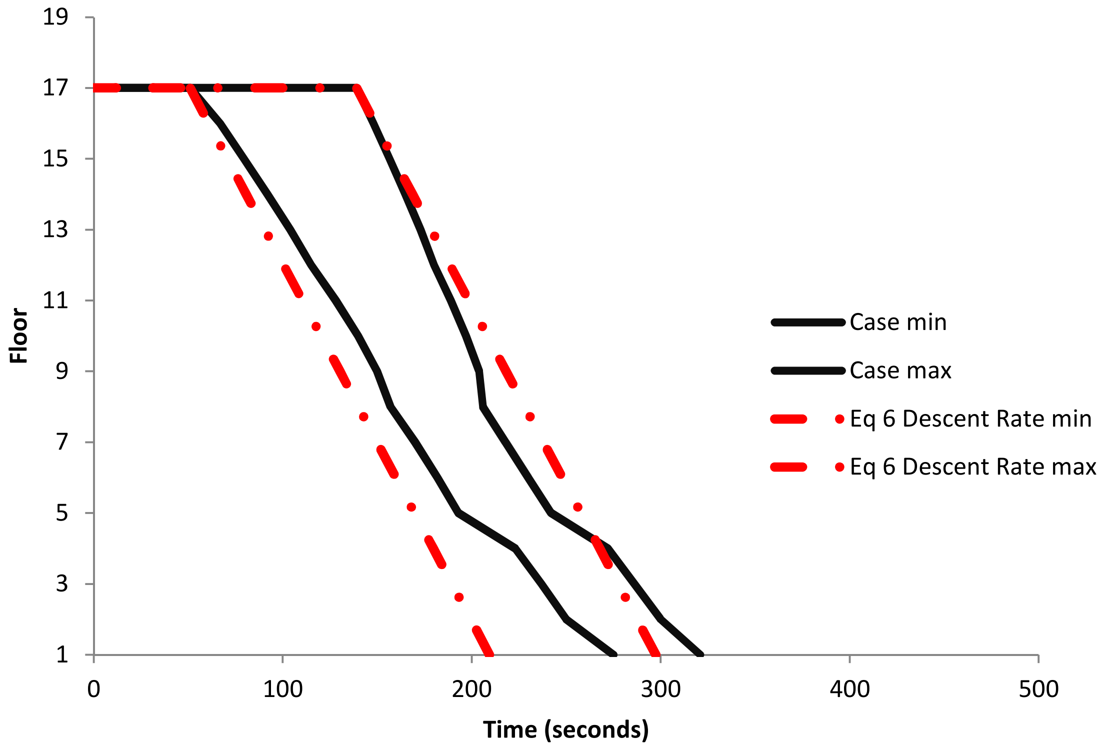


Figure III - 21: Manchester Dirty Stair Case Study Occupants Compared with the Derived Descent Rate

The total egress time prediction of equation 6 using the Manchester Dirty stair entry times are similar to the case study for both sampled occupants (Figure III - 21), except for the case study slowing near the end. The prediction line's speed of 0.92m/s is close to the one case study occupant of 0.93m/s. The other case study occupant speed is 0.71m/s; both occupants then slow to approximately 0.39m/s.

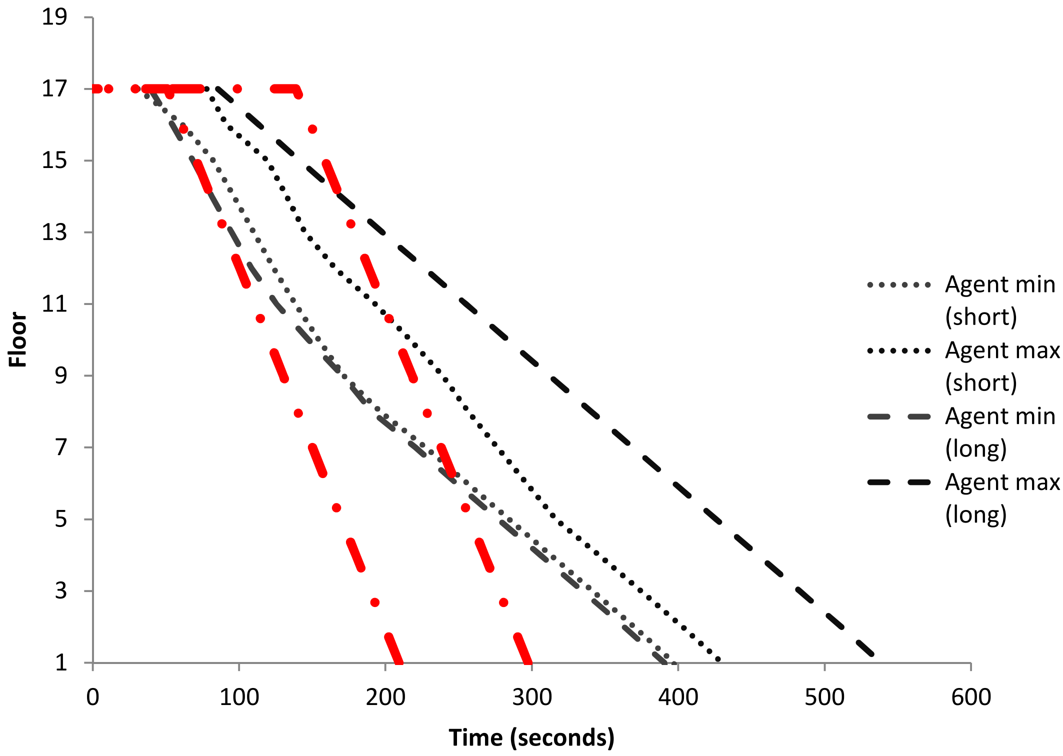


Figure III - 22: Manchester Dirty Stair Model Simulation Agents Compared with the Derived Descent Rate

Comparing to the model results, the equation 6 predicted total egress time is shorter than all of the sampled model agents (Figure III - 22). The stair entry times are still close. The prediction line's speed of 0.92m/s is faster than the estimated model agent speeds which range from 0.33 – 0.43m/s.

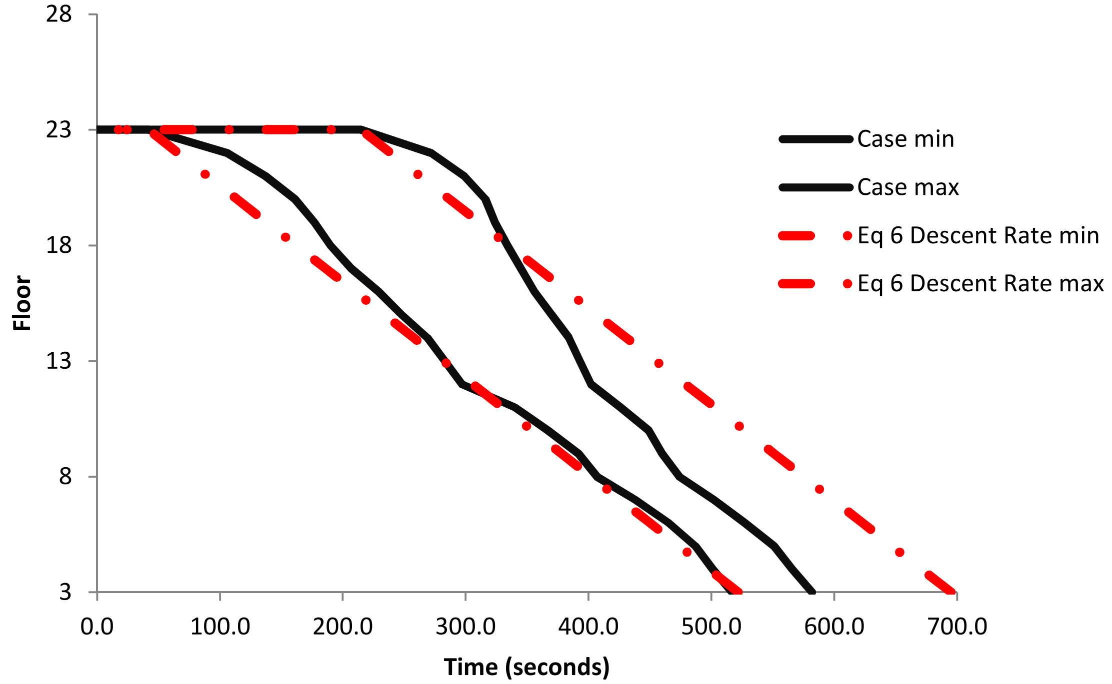


Figure III - 23: Majestic Main Stair Case Study Occupants Compared with the Derived Descent Rate

The total egress time prediction of equation 6 using the Majestic Main stair entry times are similar to the case study for the minimum prediction (Figure III - 23), the maximum prediction is longer by approximately 130 seconds. The prediction result speed of 0.5m/s is within the range of estimated case study occupant speeds, which varies from approximately 0.41 – 0.63m/s.

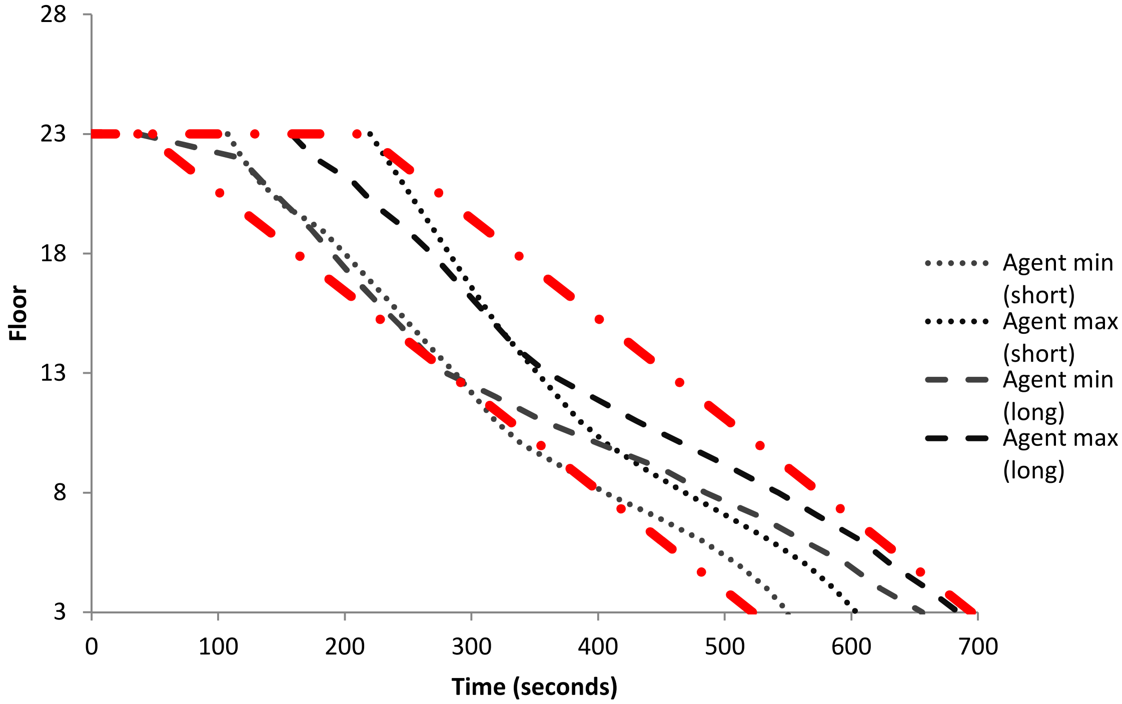


Figure III - 24: Majestic Main Stair Model Simulation Agents Compared with the Derived Descent Rate

Comparatively to the model results, the equation 6 predicted total egress time achieves similar results to the sampled model agents (Figure III - 24). The stair entry times are also close. The prediction's speed of 0.5m/s is close to the initial estimated model agent speed of 0.58m/s, however the agents slow to approximately 0.31m/s around the 13th floor.

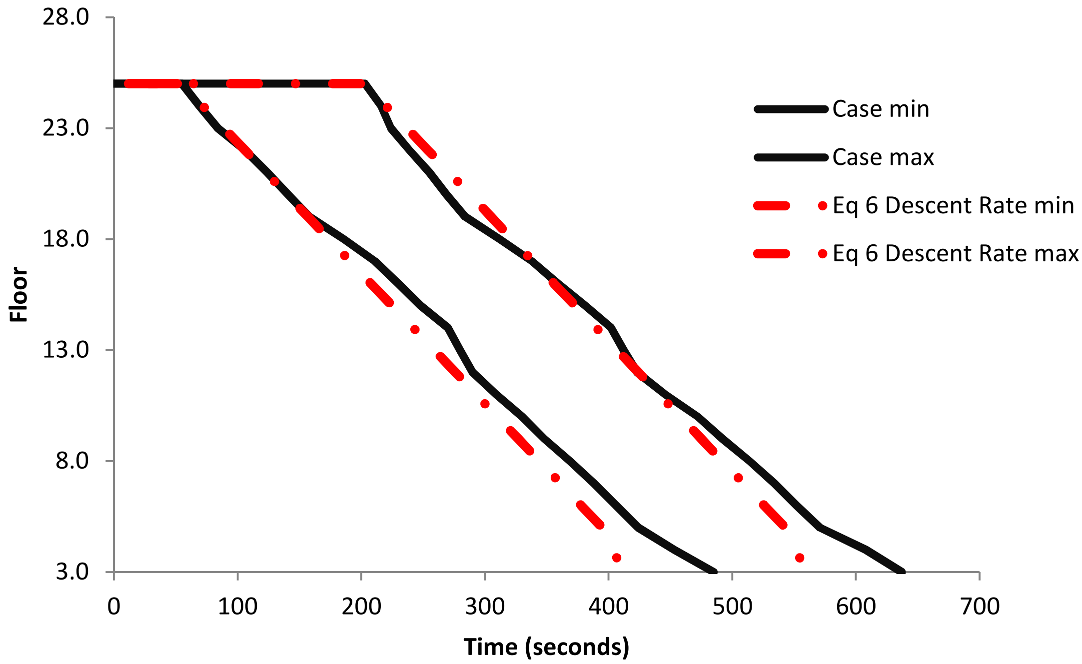


Figure III - 25: Majestic Basement Stair Case Study Occupants Compared with the Derived Descent Rate

The total egress time prediction of equation 6 using the Majestic Basement stair entry times are both similar to the case study results (Figure III - 25). The prediction result speed of 0.7m/s is close to the estimated case study occupant speed of 0.63m/s.

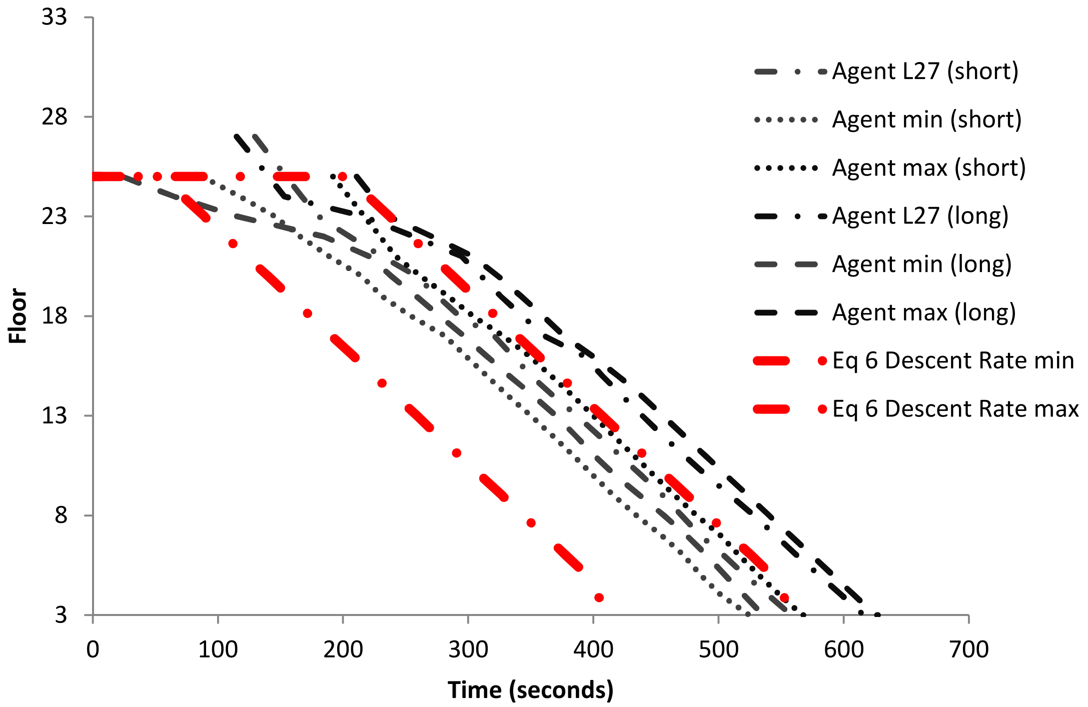


Figure III - 26: Majestic Basement Stair Model Simulation Agents Compared with the Derived Descent Rate

Comparatively to the model results, the equation 6 predicted total egress time achieves a similar result with the maximum prediction (Figure III - 26), but a shorter time with the minimum prediction. The stair entry times are however close for both stair entry times. The prediction's speed of 0.7m/s is similar to the model agents estimated speed of 0.68m/s excluding the slower speeds on the first few floors.

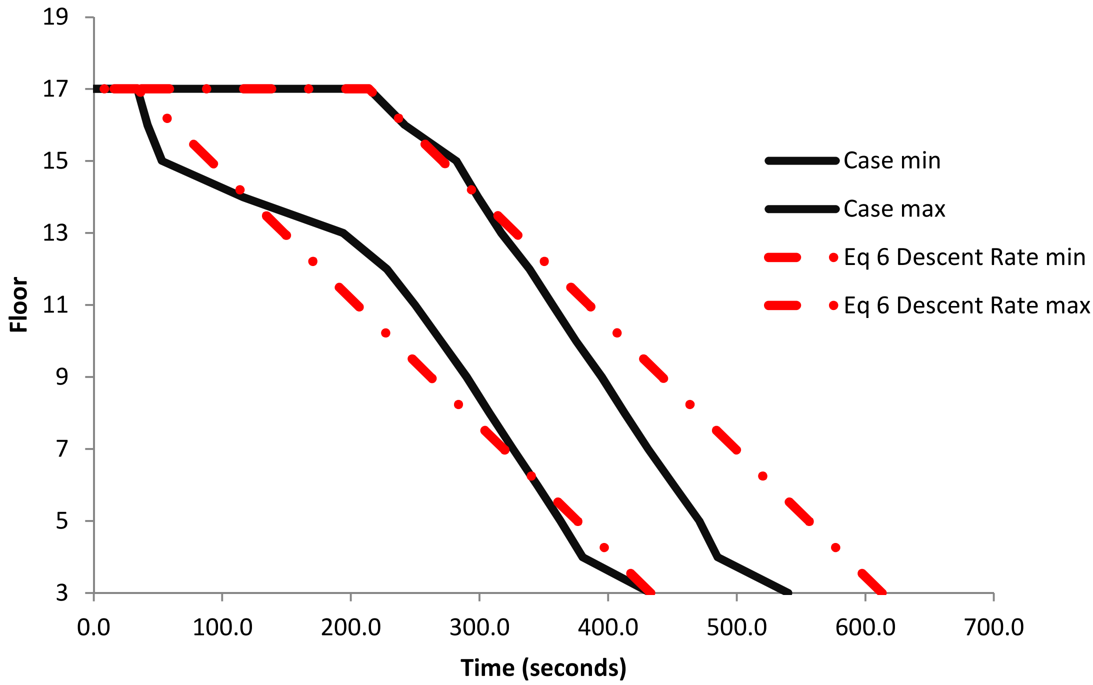


Figure III - 27: Unisys East Stair Case Study Occupants Compared with the Derived Descent Rate

The total egress time prediction of equation 6 using the Unisys East stair entry times achieves a similar result to the case study for the minimum prediction (Figure III - 27). However, the maximum prediction is longer. The prediction result speed of 0.31m/s is generally slower than the estimated case study speeds of 0.38 – 0.42m/s.

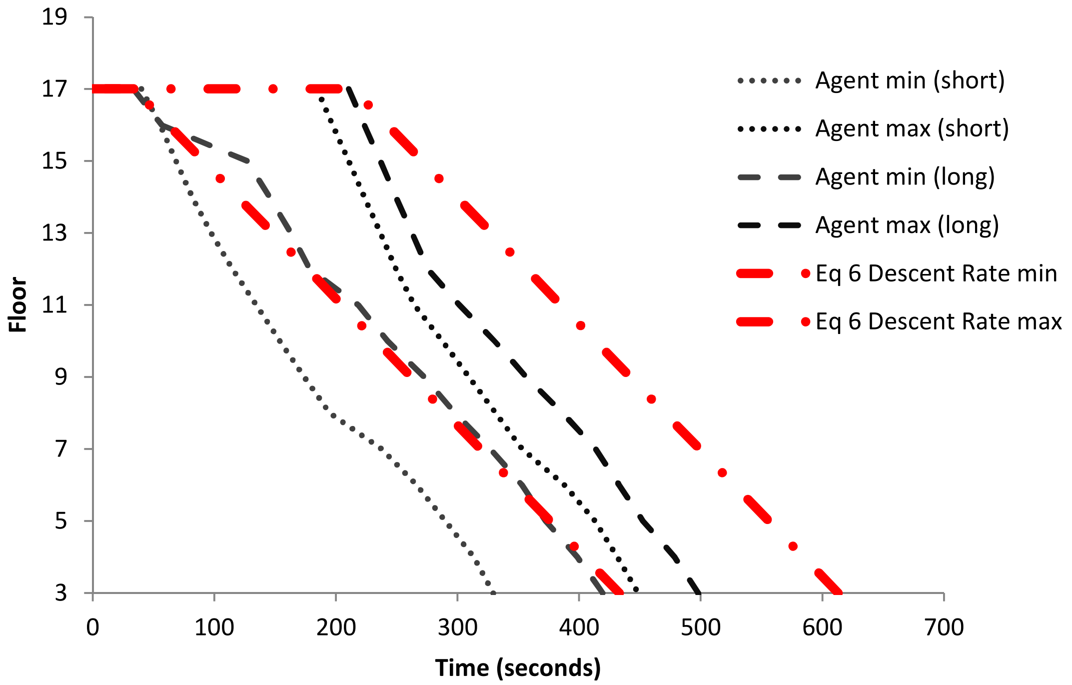


Figure III - 28: Unisys East Stair Model Simulation Agents Compared with the Derived Descent Rate

Comparatively to the model results, the equation 6 predicted total egress time achieves a similar result for the minimum prediction (Figure III - 28), but a longer time for the maximum prediction. The stair entry times are close to the model agent's. The prediction's speed of 0.31m/s is slower than the model agents who range from 0.35 – 0.41m/s. One model agent has an estimated speed of 0.67m/s.

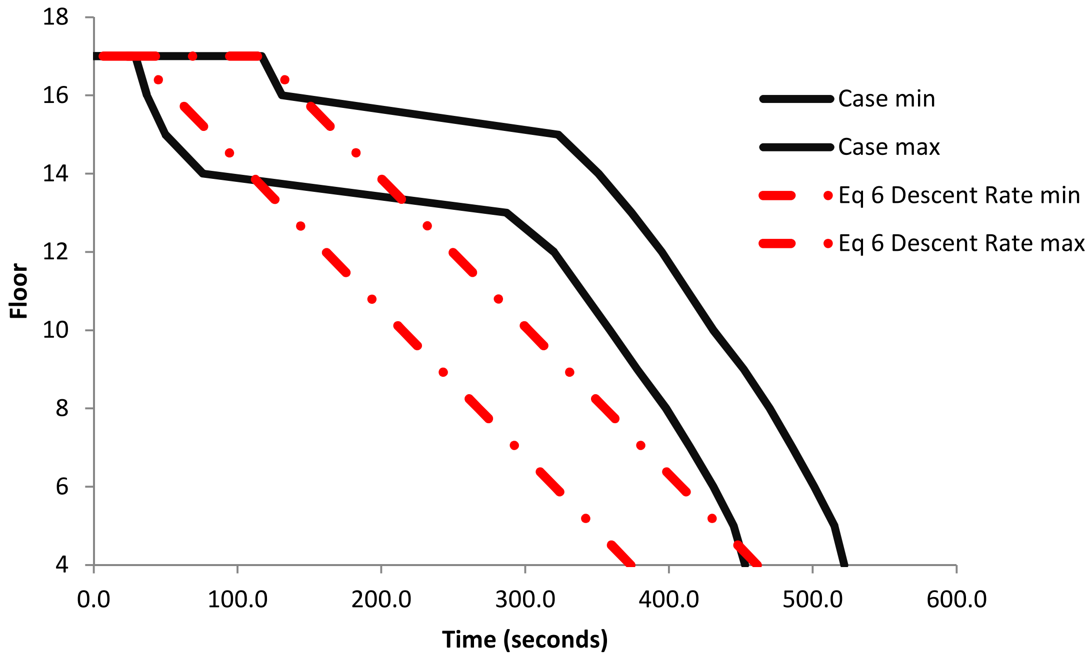


Figure III - 29: Unisys West Stair Case Study Occupants Compared with the Derived Descent Rate

The total egress time prediction of equation 6 using the Unisys West stair entry times are shorter than both the case study occupants (Figure III - 29), but not by as much as might be expected considering the delay experienced by the case study occupants . The prediction result speed of 0.33m/s is slower than the estimated case study speeds of 0.45 – 0.47m/s excluding the period of significant delay.

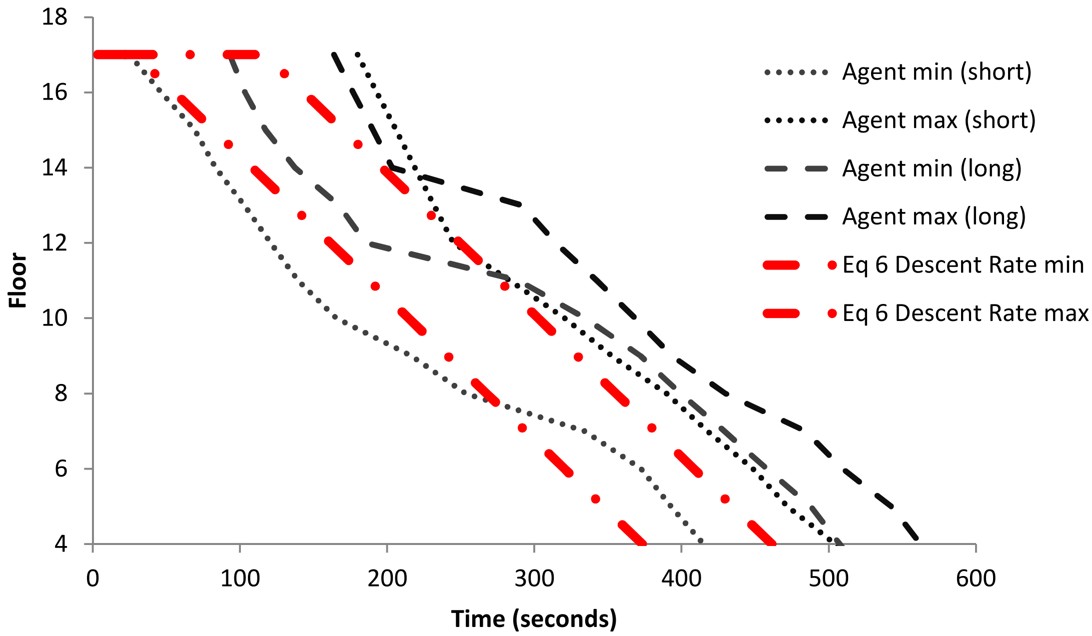


Figure III - 30: Unisys West Stair Model Simulation Agents Compared with the Derived Descent Rate

Comparatively to the model results, the equation 6 predicted total egress time achieves a generally shorter result (Figure III - 30). The stair entry times similar for the minimum prediction line, but shorter for the maximum prediction line. The prediction's speed of 0.33m/s within the range of estimated model agent speeds which start off around 0.43m/s and then slow to approximately 0.26m/s around the 13th floor.

7.1.6 Christchurch Stair Individual Descent Chart Comparisons

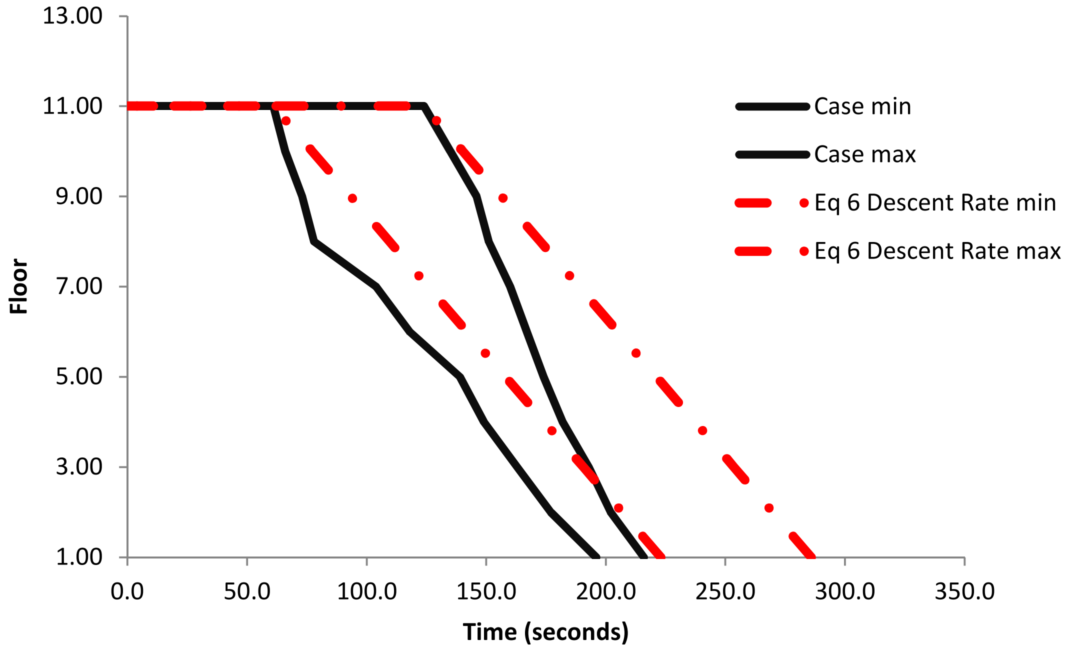


Figure III - 31: Christchurch Stair A Case Study Occupants Compared with the Derived Descent Rate

The total egress time prediction of equation 6 using the Christchurch A stair entry times are similar for the minimum prediction (Figure III - 31). The maximum prediction is longer than the case study. The prediction line's speed of 0.45m/s is slower than the estimated case study speeds, which range from 1.27m/s for the maximum stair entry occupant and 0.49m/s for the minimum stair entry occupant.

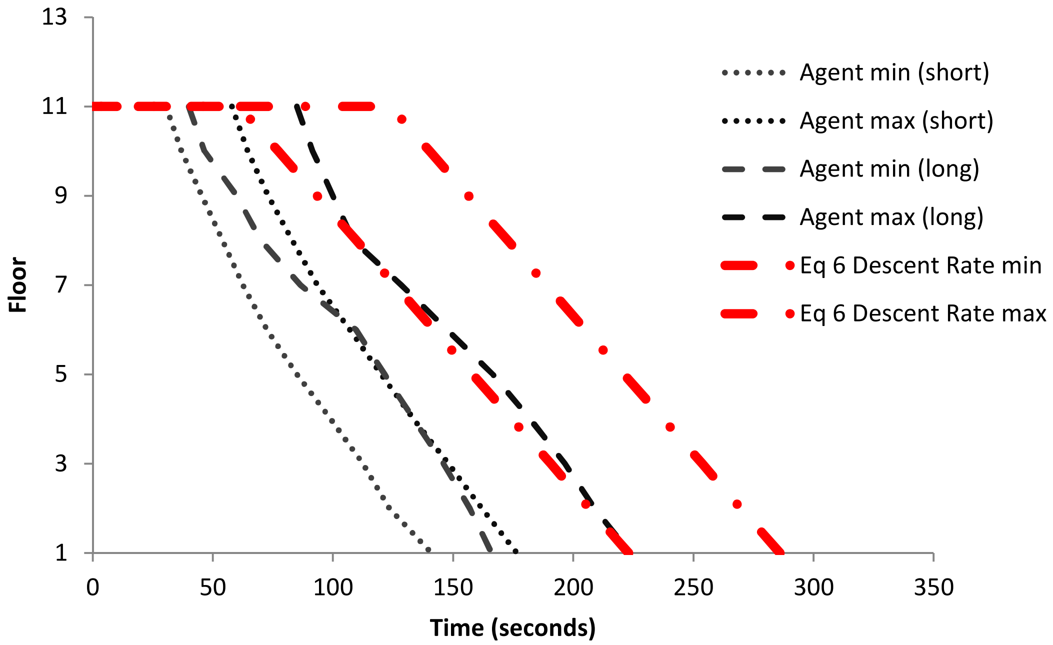


Figure III - 32: Christchurch Stair A Model Simulation Agents Compared with the Derived Descent Rate

Comparatively to the model results, the equation 6 predicted total egress time is longer than all model agents (Figure III - 32). The stair entry times are also longer. The prediction's speed of 0.45m/s is slower than the estimated model agent's which was approximately 0.6m/s. Some agents had periods of speeds which were approximately 0.94m/s and then periods of speeds of approximately 0.41m/s

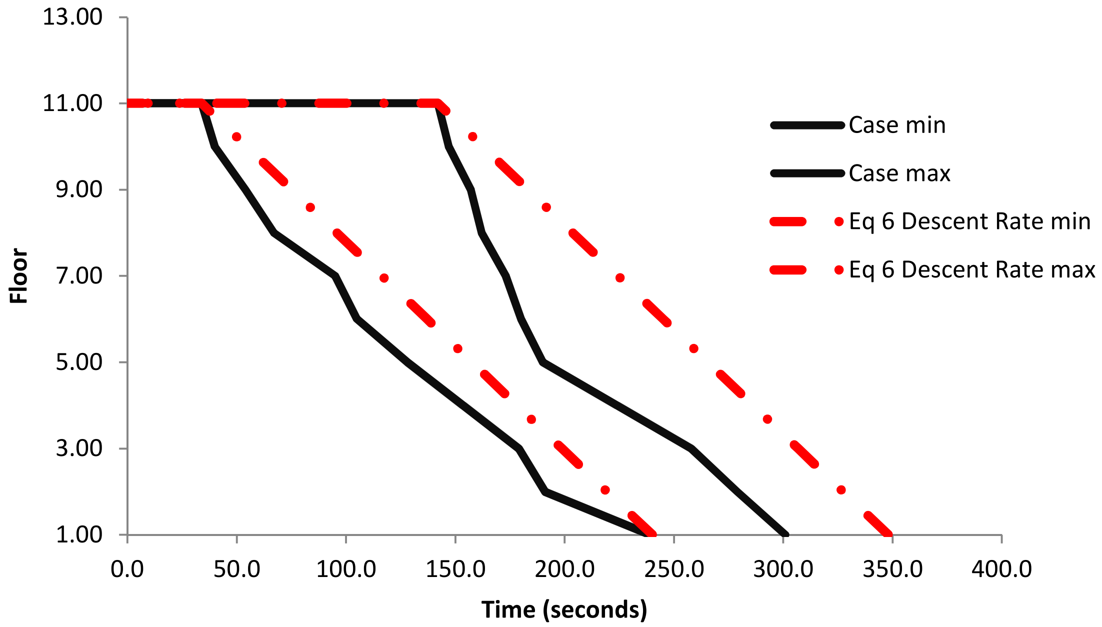


Figure III - 33: Christchurch Stair B Case Study Occupants Compared with the Derived Descent Rate

The total egress time prediction of equation 6 using the Christchurch B stair entry times are similar for the minimum prediction line, but longer for the maximum prediction line (Figure III - 33). The prediction line speed of 0.35m/s is slower than the initial speeds of the occupants which is approximately 0.9m/s, but the occupants slow to speeds of approximately 0.22 – 0.35m/s. This is slightly slower than the prediction line speed.

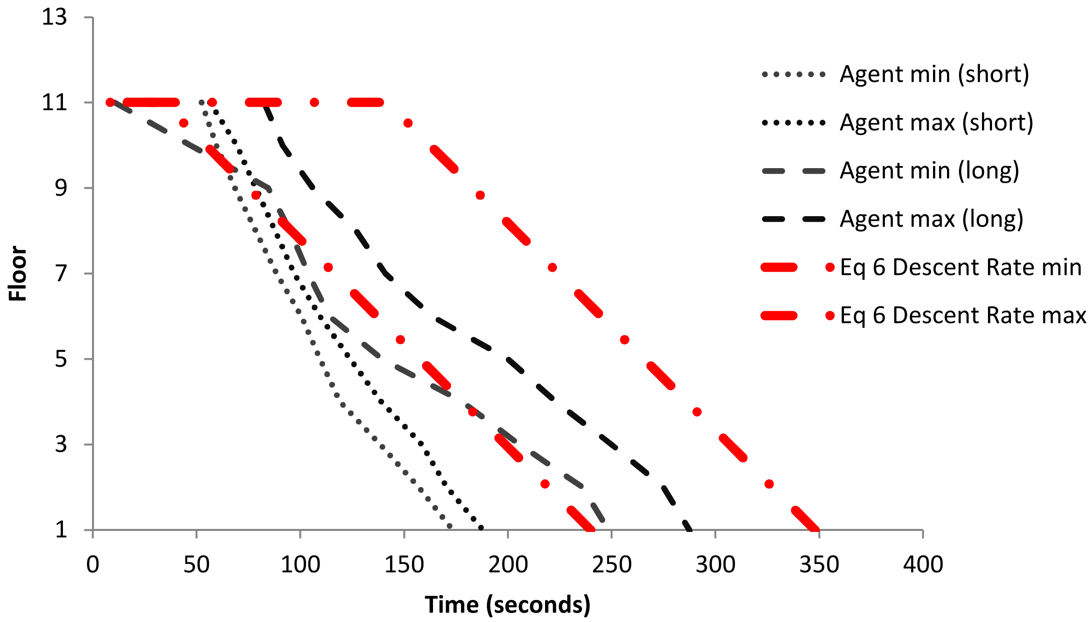


Figure III - 34: Christchurch Stair B Model Simulation Agents Compared with the Derived Descent Rate

Comparatively to the model results, the equation 6 predicted total egress time is longer than all but one model agent (Figure III - 34). The stair entry times are close for the minimum prediction line, but the maximum prediction line is longer. The prediction line's speed of 0.35m/s is slower than most of the model agent's speeds which are approximately 0.55m/s. However, two agents slow to approximately 0.2 to 0.3m/s around the 6th floor.